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The International System of Units (SI)

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Barry N. Taylor and Ambler Thompson, Editors

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Editors:
Barry N. Taylor
Physics Laboratory

Ambler Thompson
Technology Services

National Institute of Standards and Technology
Gaithersburg, MD 20899

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Foreword

The International System of Units, universally abbreviated SI (from the *French Le Système International d'Unités*), is the modern metric system of measurement. Long the dominant system used in science, the SI is rapidly becoming the dominant measurement system used in international commerce. In recognition of this fact and the increasing global nature of the marketplace, the Omnibus Trade and Competitiveness Act of 1988, which changed the name of the National Bureau of Standards (NBS) to the National Institute of Standards and Technology (NIST) and gave to NIST the added task of helping U.S. industry increase its competitiveness, designates "the metric system of measurement as the preferred system of weights and measures for United States trade and commerce."

The definitive international reference on the SI is a booklet published by the International Bureau of Weights and Measures (BIPM, *Bureau International des Poids et Mesures*) and often referred to as the BIPM SI Brochure. Entitled *Le Système International d' Unités (SI)*, the booklet is in French followed by a text in English. This 2008 edition of NIST Special Publication (SP) 330 is the United States version of the English text of the eighth edition of the Brochure (the most current) published in 2006. The 2008 edition of NIST SP 330 replaces its immediate predecessor, the 2001 edition, which was based on the seventh edition of the BIPM SI Brochure published in 1998, but including *Supplement 2000: addenda and corrigenda to the 7th edition (1998)*, published by the BIPM in June 2000.

Like its 2001 predecessor, the 2008 edition of NIST SP 330 conforms with the English text in the BIPM SI Brochure but contains a few minor differences to reflect the most recent interpretation of the SI for the United States by the Secretary of Commerce, as published in the *Federal Register* of July 28, 1998, 63 FR 40334-40340. (The Metric Conversion Act of 1975 gives the Secretary of Commerce the responsibility of interpreting or modifying the SI for use in the United States. A slightly updated version of the 1998 interpretation is expected to be published in the *Federal Register* in 2008.) These differences include the following: (i) The spelling of English words is in accordance with the *United States Government Printing Office Style Manual*, which follows *Webster's Third New International Dictionary* rather than the *Oxford Dictionary*. Thus the spellings "meter," "liter," and "deka" are used rather than "metre," "litre," and "deca" as in the original BIPM English text; (ii) the name of the unit with symbol t and defined according to 1 t = 10^3 kg is called "metric ton" rather than "tonne"; (iii) the four units curie, roentgen, rad, and rem are given in Table 10, p. 38; (iv) a number of "Editors' notes" are added in order to indicate such differences where significant (except spelling differences) and to clarify the text; and (v) a few very minor editorial changes are made in order to "Americanize" some phrases.

Because of the importance of the SI to science, technology, and commerce, and because (i) NIST coordinates the Federal Government policy on the conversion to the SI by Federal agencies and on the use of the SI by U.S. industry, (ii) NIST provides official U.S. representation in the various international bodies established by the Meter Convention (see p. 1), and (iii) the Secretary of Commerce has delegated his authority to interpret or modify the SI for use in the United States to the

NIST Director, NIST provides a number of other sources of information on the SI in addition to NIST SP 330. These include NIST Special Publication 811, *Guide for the Use of the International System of Units (SI)*, by Ambler Thompson and Barry N. Taylor; and NIST Special Publication 814, *Interpretation of the SI for the United States and Metric Conversion Policy for Federal Agencies*, Barry N. Taylor, Editor. Further, NIST SP 330, NIST SP 811, the aforementioned *Federal Register* notice, the "essentials" of the SI together with useful background information, and links to other organizations involved with the SI, for example, the NIST Laws and Metric Group and the BIPM itself, are all available on the NIST Physics Laboratory Web site entitled "NIST Reference on Constants, Units, and Uncertainty" at http://physics.nist.gov/cuu. Users of this NIST publication are encouraged to take advantage of these other sources of information.

March 2008

Barry N. Taylor

Barry N. Taylor

Ambler Thompson

Ambler Thompson

Note from the BIPM[†] on copyright and the use of the English text

"All BIPM's works are internationally protected by copyright. This document has been drafted further to a permission obtained by the BIPM. The only official text is the French text of the original document created by the BIPM."

To make its work more widely accessible, the International Committee for Weights and Measures has decided to publish an English version of its reports. Readers should note that the official record is always that of the French text. This must be used when an authoritative reference is required or when there is doubt about the interpretation of the text.

Translations complete or partial, of this brochure (or of its earlier editions) have been published in various languages, notably in Bulgarian, Chinese, Czech, English, German, Japanese, Korean, Portuguese, Romanian, and Spanish. The ISO and numerous countries have also published standards and guides to the use of SI Units.

[†] Editors'note: Acronyms used in this publication are listed with their meaning on p. 87.

The BIPM and the Meter Convention

The International Bureau of Weights and Measures (BIPM) was set up by the Meter Convention (*Convention du Mètre*) signed in Paris on 20 May 1875 by seventeen States during the final session of the diplomatic Conference of the Meter. This Convention was amended in 1921.

The BIPM has its headquarters near Paris, in the grounds (43 520 m^2) of the Pavillon de Breteuil (Parc de Saint-Cloud) placed at its disposal by the French Government; its upkeep is financed jointly by the Member States of the Meter Convention.

The task of the BIPM is to ensure worldwide unification of measurements; its function is thus to:

- establish fundamental standards and scales for the measurement of the principal physical quantities and maintain the international prototypes;
- carry out comparisons of national and international standards;
- ensure the coordination of corresponding measurement techniques;
- carry out and coordinate measurements of the fundamental physical constants relevant to these activities.

The BIPM operates under the exclusive supervision of the International Committee for Weights and Measures (CIPM) which itself comes under the authority of the General Conference on Weights and Measures (CGPM) and reports to it on the work accomplished by the BIPM.

Delegates from all Member States of the Meter Convention attend the General Conference which, at present, meets every four years. The function of these meetings is to:

- discuss and initiate the arrangements required to ensure the propagation and improvement of the International System of Units (SI), which is the modern form of the metric system;
- confirm the results of new fundamental metrological determinations and various scientific resolutions of international scope;
- take all major decisions concerning the finance, organization and development of the BIPM.

The CIPM has eighteen members each from a different State: at present, it meets every year. The officers of this committee present an annual report on the administrative and financial position of the BIPM to the Governments of the Member States of the Meter Convention. The principal task of the CIPM is to ensure

As of 31 December 2005, fifty-one States were members of this Convention: Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Cameroon, Canada, Chile, China, Czech Republic, Denmark, Dominican Republic, Egypt, Finland, France, Germany, Greece, Hungary, India, Indonesia, Iran (Islamic Rep. of), Ireland, Israel, Italy, Japan, Korea (Dem. People's Rep. of), Korea (Rep. of), Malaysia, Mexico, The Netherlands, New Zealand, Norway, Pakistan, Poland, Portugal, Romania, Russian Federation, Serbia and Montenegro, Singapore, Slovakia, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, United States, Uruguay, and Venezuela.

Twenty States and Economies were Associates of the General Conference: Belarus, CARICOM, Chinese Taipei, Costa Rica, Croatia, Cuba, Ecuador, Estonia, Hong Kong (China), Jamaica, Kazakhstan, Kenya, Latvia, Lithuania, Malta, Panama, Philippines, Slovenia, Ukraine, and Viet Nam.

worldwide uniformity in units of measurement. It does this by direct action or by submitting proposals to the CGPM.

The activities of the BIPM, which in the beginning were limited to measurements of length and mass, and to metrological studies in relation to these quantities, have been extended to standards of measurement of electricity (1927), photometry and radiometry (1937), ionizing radiation (1960), time scales (1988) and to chemistry (2000). To this end the original laboratories, built from 1876 to 1878, were enlarged in 1929; new buildings were constructed in 1963 to 1964 for the ionizing radiation laboratories, in 1984 for the laser work and in 1988 for a library and offices. In 2001 a new building for the workshop, offices and meeting rooms was opened.

Some forty-five physicists and technicians work in the BIPM laboratories. They mainly conduct metrological research, international comparisons of realizations of units and calibrations of standards. An annual report, the *Director's Report on the Activity and Management of the International Bureau of Weights and Measures*, gives details of the work in progress.

Following the extension of the work entrusted to the BIPM in 1927, the CIPM has set up bodies, known as Consultative Committees, whose function is to provide it with information on matters that it refers to them for study and advice. These Consultative Committees, which may form temporary or permanent working groups to study special topics, are responsible for coordinating the international work carried out in their respective fields and for proposing recommendations to the CIPM concerning units.

The Consultative Committees have common regulations (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **31**, 97). They meet at irregular intervals. The president of each Consultative Committee is designated by the CIPM and is normally a member of the CIPM. The members of the Consultative Committees are metrology laboratories and specialized institutes, agreed by the CIPM, which send delegates of their choice. In addition, there are individual members appointed by the CIPM, and a representative of the BIPM (Criteria for membership of Consultative Committees, *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1996, **64**, 124). At present, there are ten such committees:

1. The Consultative Committee for Electricity and Magnetism (CCEM), new name given in 1997 to the Consultative Committee for Electricity (CCE) set up in 1927;

2. The Consultative Committee for Photometry and Radiometry (CCPR), new name given in 1971 to the Consultative Committee for Photometry (CCP) set up in 1933 (between 1930 and 1933 the CCE dealt with matters concerning photometry);

3. The Consultative Committee for Thermometry (CCT), set up in 1937;

4. The Consultative Committee for Length (CCL), new name given in 1997 to the Consultative Committee for the Definition of the Meter (CCDM), set up in 1952;

5. The Consultative Committee for Time and Frequency (CCTF), new name given in 1997 to the Consultative Committee for the Definition of the Second (CCDS) set up in 1956;
6. The Consultative Committee for Ionizing Radiation (CCRI), new name given in 1997 to the Consultative Committee for Standards of Ionizing Radiation (CCEMRI) set up in 1958 (in 1969 this committee established four sections: Section I (x and γ rays, electrons), Section II (Measurement of radionuclides), Section III (Neutron measurements), Section IV (α-energy standards); in 1975 this last section was dissolved and Section II was made responsible for its field of activity;
7. The Consultative Committee for Units (CCU), set up in 1964 (this committee replaced the Commission for the System of Units set up by the CIPM in 1954);
8. The Consultative Committee for Mass and Related Quantities (CCM), set up in 1980;
9. The Consultative Committee for Amount of Substance: Metrology in chemistry (CCQM), set up in 1993;
10. The Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV), set up un 1999.

The proceedings of the General Conference and the CIPM are published by the BIPM in the following series:

- *Report of the meeting of the General Conference on Weights and Measures*;
- *Report of the meeting of the International Committee for Weights and Measures.*

The CIPM decided in 2003 that the reports of meetings of the Consultative Committees should no longer be printed, but would be placed on the BIPM website, in their original language.

The BIPM also publishes monographs on special metrological subjects and, under the title The International System of Units (SI), a brochure, periodically updated, in which are collected all the decisions and recommendations concerning units.

The collection of the *Travaux et Mémoires du Bureau International des Poids et Mesures* (22 volumes published between 1881 and 1966) and the *Recueil de Travaux du Bureau International des Poids et Mesures* (11 volumes published between 1966 and 1988) ceased by a decision of the CIPM.

The scientific work of the BIPM is published in the open scientific literature and an annual list of publications appears in the *Director's Report on the Activity and Management of the International Bureau of Weights and Measures.*

Since 1965 *Metrologia*, an international journal published under the auspices of the CIPM, has printed articles dealing with scientific metrology, improvements in methods of measurement, work on standards and units, as well as reports concerning the activities, decisions and recommendations of the various bodies created under the Meter Convention.

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The International System of Units

Contents

Preface
to the 8th edition

We have pleasure in introducing the 8th edition of this publication, commonly called the SI Brochure, which defines and presents the *Système International d'Unités*, the SI (known in English as the International System of Units). This Brochure is published as a hard copy, and is also available in electronic form at http://www.bipm.org/en/si/si_brochure/.

Since 1970, the *Bureau International des Poids et Mesures*, the BIPM (known in English as the International Bureau of Weights and Measures), has published seven previous editions of this document. Its main purpose is to define and promote the SI, which has been used around the world as the preferred language of science and technology since its adoption in 1948 through a Resolution of the 9th *Conférence Générale des Poids et Mesures*, the CGPM (known in English as the General Conference on Weights and Measures).[†]

The SI is, of course, a living system which evolves, and which reflects current best measurement practice. This 8th edition therefore contains a number of changes since the previous edition. As before, it lists the definitions of all the base units, and all the Resolutions and Recommendations of the CGPM and the *Comité International des Poids et Mesures*, the CIPM (known in English as the International Committee for Weights and Measures), relating to the International System of Units. Formal reference to CGPM and CIPM decisions are to be found in the successive volumes of the *Comptes Rendus* of the CGPM (CR) and the *Procès-Verbaux* of the CIPM (PV); many of these are also listed in *Metrologia*. To simplify practical use of the system, the text provides explanations of these decisions, and the first chapter provides a general introduction to establishing a system of units and to the SI in particular. The definitions and the practical realizations of all the units are also considered in the context of general relativity. A brief discussion of units associated with biological quantities has been introduced for the first time.

Appendix 1 reproduces, in chronological order, all the decisions (Resolutions, Recommendations, Declarations) promulgated since 1889 by the CGPM and the CIPM on units of measurement and the International System of Units.

Appendix 2 exists only in the electronic version, which is available at http://www.bipm.org/en/si/si_brochure/appendix2/. It outlines the practical realization of some important units, consistent with the definitions given in the principal text, which metrological laboratories can make to realize physical units and to calibrate material standards and measuring instruments of the highest quality. This

[†] Editors' note: The 9th CGPM in 1948 initiated the study that led to the formal establishment of the SI by the 11th CGPM in 1960.

appendix will be updated regularly to reflect improvements in the experimental techniques for realizing the units.

Appendix 3 presents units used to measure actinic effects in biological materials.

The *Comité Consultatif des Unités* of the CIPM, the CCU (known in English as the Consultative Committee for Units), was responsible for drafting this document, and both the CCU and the CIPM approved the final text. This 8th edition is a revision of the 7th edition (1998); it takes into consideration decisions made by the CGPM and the CIPM since the 7th edition was published.

For more than thirty-five years this document has been used as a work of reference in many countries, organizations, and scientific unions. To make its contents accessible to a greater number of readers, the CIPM decided, in 1985, to include an English version of the text in the 5th edition; this double presentation is continued in all later editions. For the first English version the BIPM endeavoured to produce a faithful translation of the French original by close collaboration with the National Physical Laboratory (Teddington, United Kingdom) and the National Institute of Standards and Technology (Gaithersburg, United States), at that time the National Bureau of Standards. For the present edition the French and English versions were prepared by the CCU in close collaboration with the BIPM.

The 22nd CGPM decided, in 2003, following a decision of the CIPM in 1997, that "the symbol for the decimal marker shall be either the point on the line or the comma on the line". Following this decision, and following custom in the two languages, in this edition the point on the line is used as a decimal marker in the English text, and a comma on the line is used in the French text. This has no implication for the translation of the decimal marker into other languages. A point to note is that small spelling variations occur in the language of the English speaking countries (for instance, "metre" and "meter", "litre" and "liter")[†]. In this respect, the English text presented here follows the International Standard ISO 31, *Quantities and Units*.

Readers should note that the official record is always that of the French text. This must be used when an authoritative reference is required or when there is doubt about the interpretation of the text.

March 2006

E. Göbel *President, CIPM*	I. M. Mills *President, CCU*	A. J. Wallard *Director, BIPM*

[†] Editors' note: See the Foreword regarding the spelling of English words in this United States version of the BIPM SI Brochure.

1 Introduction

1.1 Quantities and units

The value of a quantity is generally expressed as the product of a number and a unit. The unit is simply a particular example of the quantity concerned which is used as a reference, and the number is the ratio of the value of the quantity to the unit. For a particular quantity, many different units may be used. For example, the speed v of a particle may be expressed in the form $v = 25$ m/s $= 90$ km/h, where meter per second and kilometer per hour are alternative units for expressing the same value of the quantity speed. However, because of the importance of a set of well defined and easily accessible units universally agreed for the multitude of measurements that support today's complex society, units should be chosen so that they are readily available to all, are constant throughout time and space, and are easy to realize with high accuracy.

The terms **quantity** and **unit** are defined in the *International Vocabulary of Basic and General Terms in Metrology*, the VIM.

In order to establish a system of units, such as the International System of Units, the SI, it is necessary first to establish a system of quantities, including a set of equations defining the relations between those quantities. This is necessary because the equations between the quantities determine the equations relating the units, as described below. It is also convenient to choose definitions for a small number of units that we call *base units*, and then to define units for all other quantities as products of powers of the base units that we call *derived units*. In a similar way the corresponding quantities are described as *base quantities* and *derived quantities*, and the equations giving the derived quantities in terms of the base quantities are used to determine the expression for the derived units in terms of the base units, as discussed further in Section 1.4 below. Thus in a logical development of this subject, the choice of quantities and the equations relating the quantities comes first, and the choice of units comes second.

The quantity speed, v, may be expressed in terms of the quantities distance, x, and time, t, by the equation

$$v = \mathrm{d}x/\mathrm{d}t.$$

In most systems of quantities and units, distance x and time t are regarded as base quantities, for which the meter, m, and the second, s, may be chosen as base units. Speed v is then taken as a derived quantity, with the derived unit meter per second, m/s.

From a scientific point of view, the division of quantities into base quantities and derived quantities is a matter of convention, and is not essential to the physics of the subject. However for the corresponding units, it is important that the definition of each base unit is made with particular care, to satisfy the requirements outlined in the first paragraph above, since they provide the foundation for the entire system of units. The definitions of the derived units in terms of the base units then follow from the equations defining the derived quantities in terms of the base quantities. Thus the establishment of a system of units, which is the subject of this brochure, is intimately connected with the algebraic equations relating the corresponding quantities.

For example, in electrochemistry, the electric mobility of an ion, u, is defined as the ratio of its velocity v to the electric field strength, E: $u = v/E$. The derived unit of electric mobility is then given as $(\mathrm{m/s})/(\mathrm{V/m}) = \mathrm{m^2\ V^{-1}\ s^{-1}}$, in units which may be easily related to the chosen base units (V is the symbol for the SI derived unit volt).

The number of derived quantities of interest in science and technology can, of course, be extended without limit. As new fields of science develop, new quantities are devised by researchers to represent the interests of the field, and with these new quantities come new equations relating them to those quantities that were previously familiar, and hence ultimately to the base quantities. In this way the derived units to be used with the new quantities may always be defined as products of powers of the previously chosen base units.

1.2 The International System of Units (SI) and the corresponding system of quantities

This Brochure is concerned with presenting the information necessary to define and use the International System of Units, universally known as the SI (from the French *Système International d'Unités*). The SI was established by and is defined by the General Conference on Weights and Measures, the CGPM, as described in the Historical note in Section 1.8 below*.

The name *Système International d'Unités*, and the abbreviation SI, were established by the 11th CGPM in 1960.

The system of quantities, including the equations relating the quantities, to be used with the SI, is in fact just the quantities and equations of physics that are familiar to all scientists, technologists, and engineers. They are listed in many textbooks and in many references, but any such list can only be a selection of the possible quantities and equations, which is without limit. Many of the quantities, their recommended names and symbols, and the equations relating them, are listed in the International Standards ISO 31 and IEC 60027 produced by Technical Committee 12 of the International Organization for Standardization, ISO/TC 12, and by Technical Committee 25 of the International Electrotechnical Commission, IEC/TC 25. The ISO 31 and IEC 60027 Standards are at present being revised by the two standardization organizations in collaboration. The revised harmonized standard will be known as ISO/IEC 80000, *Quantities and Units*, in which it is proposed that the quantities and equations used with the SI will be known as the International System of Quantities.

Examples of the equations relating quantities used in the SI are the Newtonian inertial equation relating force, F, to mass, m, and acceleration, a, for a particle: $F = ma$, and the equation giving the kinetic energy, T, of a particle moving with velocity, v: $T = mv^2/2$.

The base quantities used in the SI are length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity. The base quantities are by convention assumed to be independent. The corresponding base units of the SI were chosen by the CGPM to be the meter, the kilogram, the second, the ampere, the kelvin, the mole, and the candela. The definitions of these base units are presented in Section 2.1.1 in the following chapter. The derived units of the SI are then formed as products of powers of the base units, according to the algebraic relations that define the corresponding derived quantities in terms of the base quantities, see Section 1.4 below.

On rare occasions a choice may arise between different forms of the relations between the quantities. An important example occurs in defining the electromagnetic quantities. In this case the rationalized four-quantity electromagnetic equations used with the SI are based on length, mass, time, and electric current. In these equations, the electric constant ε_0 (the permittivity of vacuum) and the magnetic constant μ_0 (the permeability of vacuum) have

* Acronyms used in this Brochure are listed with their meaning on p. 87.

dimensions and values such that $\varepsilon_0\mu_0 = 1/c_0^2$, where c_0 is the speed of light in vacuum. The Coulomb law of electrostatic force between two particles with charges q_1 and q_2 separated by a distance r is written**

$$\boldsymbol{F} = \frac{q_1 q_2\,\boldsymbol{r}}{4\pi\varepsilon_0 r^3}$$

and the corresponding equation for the magnetic force between two thin wire elements carrying electric currents, $i_1\mathrm{d}\boldsymbol{l}_1$ and $i_2\mathrm{d}\boldsymbol{l}_2$, is written

$$\mathrm{d}^2\boldsymbol{F} = \frac{\mu_0}{4\pi}\,\frac{i_1\mathrm{d}\boldsymbol{l}_1 \times (i_2\mathrm{d}\boldsymbol{l}_2 \times \boldsymbol{r})}{r^3}$$

where $\mathrm{d}^2\boldsymbol{F}$ is the double differential of the force $\boldsymbol{F}$. These equations, on which the SI is based, are different from those used in the CGS-ESU (electrostatic), CGS-EMU (electromagnetic), and CGS-Gaussian systems, where ε_0 and μ_0 are dimensionless quantities, chosen to be equal to one, and where the rationalizing factors of 4π are omitted.

Editors' Note : A non-SI system of units is the CGS (centimeter-gram-second) System. There are several versions of CGS units used for electricity and magnetism: electrostatic units (ESU), electromagnetic units (EMU), and Gaussian units. See discussion associated with Table 9.

1.3 Dimensions of quantities

By convention physical quantities are organized in a system of dimensions. Each of the seven base quantities used in the SI is regarded as having its own dimension, which is symbolically represented by a single sans serif roman capital letter. The symbols used for the base quantities, and the symbols used to denote their dimension, are given as follows.

Base quantities and dimensions used in the SI

Base quantity	Symbol for quantity	Symbol for dimension
length	l, x, r, etc.	L
mass	m	M
time, duration	t	T
electric current	I, i	I
thermodynamic temperature	T	Θ
amount of substance	n	N
luminous intensity	I_v	J

Quantity symbols are always written in an italic font, and symbols for dimensions in sans-serif roman capitals.
For some quantities a variety of alternative symbols may be used, as indicated for length and electric current.
Note that symbols for quantities are only *recommendations*, in contrast to symbols for units that appear elsewhere in this brochure whose style and form is *mandatory* (see Chapter 5).

All other quantities are derived quantities, which may be written in terms of the base quantities by the equations of physics. The dimensions of the derived quantities are written as products of powers of the dimensions of the base quantities using the equations that relate the derived quantities to the base quantities. In general the dimension of any quantity Q is written in the form of a dimensional product,

$$\dim Q = \mathsf{L}^\alpha\,\mathsf{M}^\beta\,\mathsf{T}^\gamma\,\mathsf{I}^\delta\,\Theta^\varepsilon\,\mathsf{N}^\zeta\,\mathsf{J}^\eta$$

where the exponents α, β, γ, δ, ε, ζ, and η, which are generally small integers which can be positive, negative or zero, are called the dimensional exponents. The dimension of a derived quantity provides the same information about the relation of

Dimensional symbols and exponents are manipulated using the ordinary rules of algebra. For example, the dimension of area is written as L^2; the dimension of velocity as LT^{-1}; the dimension of force as LMT^{-2}; and the dimension of energy is written as $\mathsf{L}^2\mathsf{MT}^{-2}$.

** Symbols in bold print are used to denote vectors.

that quantity to the base quantities as is provided by the SI unit of the derived quantity as a product of powers of the SI base units.

There are some derived quantities Q for which the defining equation is such that all of the dimensional exponents in the expression for the dimension of Q are zero. This is true, in particular, for any quantity that is defined as the ratio of two quantities of the same kind. Such quantities are described as being *dimensionless*, or alternatively as being *of dimension one*. The coherent derived unit for such dimensionless quantities is always the number one, 1, since it is the ratio of two identical units for two quantities of the same kind.

For example, refractive index is defined as the ratio of the speed of light in vacuum to that in the medium, and is thus a ratio of two quantities of the same kind. It is therefore a dimensionless quantity. Other examples of dimensionless quantities are plane angle, mass fraction, relative permittivity, relative permeability, and finesse of a Fabry-Perot cavity.

There are also some quantities that cannot be described in terms of the seven base quantities of the SI at all, but have the nature of a count. Examples are number of molecules, degeneracy in quantum mechanics (the number of independent states of the same energy), and the partition function in statistical thermodynamics (the number of thermally accessible states). Such counting quantities are also usually regarded as dimensionless quantities, or quantities of dimension one, with the unit one, 1.

1.4 Coherent units, derived units with special names, and the SI prefixes

Derived units are defined as products of powers of the base units. When the product of powers includes no numerical factor other than one, the derived units are called *coherent derived* units. The base and coherent derived units of the SI form a coherent set, designated the set of *coherent SI units*. The word coherent is used here in the following sense: when coherent units are used, equations between the numerical values of quantities take exactly the same form as the equations between the quantities themselves. Thus if only units from a coherent set are used, conversion factors between units are never required.

The expression for the coherent unit of a derived quantity may be obtained from the dimensional product of that quantity by replacing the symbol for each dimension by the symbol of the corresponding base unit.

Some of the coherent derived units in the SI are given special names, to simplify their expression (see 2.2.2, p. 25). It is important to emphasize that each physical quantity has only one coherent SI unit, even if this unit can be expressed in different forms by using some of the special names and symbols. The inverse, however, is not true: in some cases the same SI unit can be used to express the values of several different quantities (see p. 26).

As an example of a special name, the particular combination of base units $m^2\ kg\ s^{-2}$ for energy is given the special name joule, symbol J, where by definition $J = m^2\ kg\ s^{-2}$.

The CGPM has, in addition, adopted a series of prefixes for use in forming the decimal multiples and submultiples of the coherent SI units (see 3.1, p. 29, where the prefix names and symbols are listed). These are convenient for expressing the values of quantities that are much larger than or much smaller than the coherent unit. Following the CIPM Recommendation 1 (1969) (see p. 64) these are given the name *SI prefixes*. (These prefixes are also sometimes used with other non-SI units, as described in Chapter 4 below.) However when prefixes are used with coherent SI units, the resulting units are no longer coherent, because a prefix on a coherent unit,

The length of a chemical bond is more conveniently given in nanometers, nm, than in meters, m; and the distance from London to Paris is more conveniently given in kilometers, km, than in meters, m.

either base or derived, effectively introduces a numerical factor in the expression for the unit in terms of the base units.†

As an exception, the name of the kilogram, which is the base unit of mass, includes the prefix kilo, for historical reasons. It is nonetheless taken to be a base unit of the SI. The multiples and submultiples of the kilogram are formed by attaching prefix names to the unit name "gram", and prefix symbols to the unit symbol "g" (see 3.2, p. 30). Thus 10^{-6} kg is written as a milligram, mg, not as a microkilogram, µkg.

The complete set of SI units, including both the coherent set and the multiples and submultiples of these units formed by combining them with the SI prefixes, are designated as the *complete set of SI units*, or simply the *SI units*, or the *units of the SI*. Note, however, that the decimal multiples and submultiples of the SI units do not form a coherent set.

The meter per second, symbol m/s, is the coherent SI unit of speed. The kilometer per second, km/s, the centimeter per second, cm/s, and the millimeter per second, mm/s, are also SI units, but they are not coherent SI units.

1.5 SI units in the framework of general relativity

The definitions of the base units of the SI were adopted in a context that takes no account of relativistic effects. When such account is taken, it is clear that the definitions apply only in a small spatial domain sharing the motion of the standards that realize them. These units are known as *proper units*; they are realized from local experiments in which the relativistic effects that need to be taken into account are those of special relativity. The constants of physics are local quantities with their values expressed in proper units.

The question of proper units is addressed in Resolution A4 adopted by the XXIst General Assembly of the International Astronomical Union (IAU) in 1991 and by the report of the CCDS Working Group on the Application of General Relativity to Metrology (*Metrologia*, 1997, **34**, 261-290).

Physical realizations of the definition of a unit are usually compared locally. For frequency standards, however, it is possible to make such comparisons at a distance by means of electromagnetic signals. To interpret the results the theory of general relativity is required since it predicts, among other things, a relative frequency shift between standards of about 1 part in 10^{16} per meter of altitude difference at the surface of the Earth. Effects of this magnitude cannot be neglected when comparing the best frequency standards.

1.6 Units for quantities that describe biological effects

Units for quantities that describe biological effects are often difficult to relate to units of the SI because they typically involve weighting factors that may not be precisely known or defined, and which may be both energy and frequency dependent. These units, which are not SI units, are described briefly in this section.

Optical radiation may cause chemical changes in living or non-living materials: this property is called *actinism* and radiation capable of causing such changes is referred to as *actinic radiation*. In some cases, the results of measurements of photochemical and photobiological quantities of this kind can be expressed in terms of SI units. This is discussed briefly in Appendix 3.

Sound causes small pressure fluctuations in the air, superimposed on the normal atmospheric pressure, that are sensed by the human ear. The sensitivity of the ear depends on the frequency of the sound, but is not a simple function of either the

† Editors' note: This last sentence has been slightly modified for clarity.

pressure changes or the frequency. Therefore frequency-weighted quantities are used in acoustics to approximate the way in which sound is perceived. Such frequency-weighted quantities are employed, for example, in work to protect against hearing damage. The effects of ultrasonic acoustic waves pose similar concerns in medical diagnosis and therapy.

Ionizing radiation deposits energy in irradiated matter. The ratio of deposited energy to mass is termed *absorbed dose*. High doses of ionizing radiation kill cells, and this is used in radiation therapy. Appropriate biological weighting functions are used to compare therapeutic effects of different radiation treatments. Low sub-lethal doses can cause damage to living organisms, for instance by inducing cancer. Appropriate risk-weighted functions are used at low doses as the basis of radiation protection regulations.

There is a class of units for quantifying the biological activity of certain substances used in medical diagnosis and therapy that cannot yet be defined in terms of the units of the SI. This is because the mechanism of the specific biological effect that gives these substances their medical use is not yet sufficiently well understood for it to be quantifiable in terms of physico-chemical parameters. In view of their importance for human health and safety, the World Health Organization (WHO) has taken responsibility for defining WHO International Units (IU) for the biological activity of such substances.

1.7 Legislation on units

By legislation, individual countries have established rules concerning the use of units on a national basis, either for general use or for specific areas such as commerce, health, public safety, and education. In almost all countries this legislation is based on the International System of Units.

The *Organisation Internationale de Métrologie Légale* (OIML), founded in 1955, is charged with the international harmonization of this legislation.

1.8 Historical note

The previous paragraphs of this chapter give a brief overview of the way in which a system of units, and the International System of Units in particular, is established. This note gives a brief account of the historical development of the International System.

The 9th CGPM (1948, Resolution 6; CR, 64) instructed the CIPM:

- to study the establishment of a complete set of rules for units of measurement;
- to find out for this purpose, by official enquiry, the opinion prevailing in scientific, technical and educational circles in all countries;
- to make recommendations on the establishment of a *practical system of units of measurement* suitable for adoption by all signatories to the Meter Convention.

The same CGPM also laid down, in Resolution 7 (CR, 70), general principles for the writing of unit symbols, and listed some coherent derived units which were assigned special names.

The 10th CGPM (1954, Resolution 6; CR, 80) and the 14th CGPM (1971, Resolution 3, CR, 78, and *Metrologia*, 1972, **8**, 36) adopted as base units of this practical system of units the units of the following seven quantities: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity.

The 11th CGPM (1960, Resolution 12; CR, 87) adopted the name *Système International d'Unités*, with the international abbreviation SI, for this practical system of units and laid down rules for prefixes, derived units, and the former supplementary units, and other matters; it thus established a comprehensive specification for units of measurement. Subsequent meetings of the CGPM and CIPM have added to, and modified as necessary, the original structure of the SI to take account of advances in science and of the needs of users.

The historical sequence that led to these important CGPM decisions may be summarized as follows.

- The creation of the decimal metric system at the time of the French Revolution and the subsequent deposition of two platinum standards representing the meter and the kilogram, on 22 June 1799, in the *Archives de la République* in Paris can be seen as the first step in the development of the present International System of Units.
- In 1832, Gauss strongly promoted the application of this metric system, together with the second defined in astronomy, as a coherent system of units for the physical sciences. Gauss was the first to make *absolute* measurements of the Earth's magnetic field in terms of a decimal system based on the *three mechanical units* millimeter, gram, and second for, respectively, the quantities length, mass, and time. In later years, Gauss and Weber extended these measurements to include other electrical phenomena.
- These applications in the field of electricity and magnetism were further developed in the 1860s under the active leadership of Maxwell and Thomson through the British Association for the Advancement of Science (BAAS). They formulated the requirement for a *coherent system of units* with *base* units and *derived* units. In 1874 the BAAS introduced the *CGS system*, a three-dimensional coherent unit system based on the three mechanical units centimeter, gram, and second, using prefixes ranging from micro to mega to express decimal submultiples and multiples. The subsequent development of physics as an experimental science was largely based on this system.
- The sizes of the coherent CGS units in the fields of electricity and magnetism proved to be inconvenient so, in the 1880s, the BAAS and the International Electrical Congress, predecessor of the International Electrotechnical Commission (IEC), approved a mutually coherent set of *practical units*. Among them were the ohm for electrical resistance, the volt for electromotive force, and the ampere for electric current.

- After the signing of the Meter Convention on 20 May 1875, which created the BIPM and established the CGPM and the CIPM, work began on the construction of new international prototypes of the meter and kilogram. In 1889 the first CGPM sanctioned the international prototypes for the meter and the kilogram. Together with the astronomical second as the unit of time, these units constituted a three-dimensional mechanical unit system similar to the CGS system, but with the base units meter, kilogram, and second, the MKS system.
- In 1901 Giorgi showed that it is possible to combine the mechanical units of this meter-kilogram-second system with the practical electrical units to form a single coherent four-dimensional system by adding to the three base units a fourth unit, of an electrical nature such as the ampere or the ohm, and rewriting the equations occurring in electromagnetism in the so-called rationalized form. Giorgi's proposal opened the path to a number of new developments.
- After the revision of the Meter Convention by the 6th CGPM in 1921, which extended the scope and responsibilities of the BIPM to other fields in physics, and the subsequent creation of the Consultative Committee for Electricity (CCE) by the 7th CGPM in 1927, the Giorgi proposal was thoroughly discussed by the IEC, the International Union of Pure and Applied Physics (IUPAP), and other international organizations. This led the CCE to propose, in 1939, the adoption of a four-dimensional system based on the meter, kilogram, second, and ampere, the MKSA system, a proposal approved by the CIPM in 1946.
- Following an international enquiry by the BIPM, which began in 1948, the 10th CGPM, in 1954, approved the introduction of the *ampere*, the *kelvin*, and the *candela* as base units, respectively, for electric current, thermodynamic temperature, and luminous intensity. The name *Système International d'Unités*, with the abbreviation SI, was given to the system by the 11th CGPM in 1960. At the 14th CGPM in 1971, after lengthy discussions between physicists and chemists, the current version of the SI was completed by adding the *mole* as the base unit for amount of substance, bringing the total number of base units to seven.

2 SI units

2.1 SI base units

Formal definitions of all SI base units are adopted by the CGPM. The first two definitions were adopted in 1889, and the most recent in 1983. These definitions are modified from time to time as science advances.

2.1.1 Definitions

Current definitions of the base units, as taken from the *Comptes Rendus* (CR) of the corresponding CGPM, are shown below indented and in a heavy sans-serif font. Related decisions which clarify these definitions but are not formally part of them, as taken from the *Comptes Rendus* of the corresponding CGPM or the *Procès-Verbaux* (PV) of the CIPM, are also shown indented but in a sans-serif font of normal weight. The linking text provides historical notes and explanations, but is not part of the definitions themselves.

It is important to distinguish between the definition of a unit and its realization. The definition of each base unit of the SI is carefully drawn up so that it is unique and provides a sound theoretical basis upon which the most accurate and reproducible measurements can be made. The realization of the definition of a unit is the procedure by which the definition may be used to establish the value and associated uncertainty of a quantity of the same kind as the unit. A description of how the definitions of some important units are realized in practice is given on the BIPM website,

http://www.bipm.org/en/si/si_brochure/appendix2/.

A coherent SI derived unit is defined uniquely only in terms of SI base units. For example, the coherent SI derived unit of resistance, the ohm, symbol Ω, is uniquely defined by the relation $\Omega = m^2\ kg\ s^{-3}\ A^{-2}$, which follows from the definition of the quantity electrical resistance. However any method consistent with the laws of physics could be used to realize any SI unit. For example, the unit ohm can be realized with high accuracy using the quantum Hall effect and the value of the von Klitzing constant recommended by the CIPM (see pp. 73 and 76, respectively, Appendix 1).

Finally, it should be recognized that although the seven base quantities – length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity – are by convention regarded as independent, their respective base units – the meter, kilogram, second, ampere, kelvin, mole, and candela – are in a number of instances interdependent. Thus the definition of the meter incorporates the second; the definition of the ampere incorporates the meter, kilogram, and second; the definition of the mole incorporates the kilogram; and the definition of the candela incorporates the meter, kilogram, and second.

2.1.1.1 Unit of length (meter)

The 1889 definition of the meter, based on the international prototype of platinum-iridium, was replaced by the 11th CGPM (1960) using a definition based on the wavelength of krypton 86 radiation. This change was adopted in order to improve the accuracy with which the definition of the meter could be realized, the realization being achieved using an interferometer with a travelling microscope to measure the optical path difference as the fringes were counted. In turn, this was replaced in 1983 by the 17th CGPM (1983, Resolution 1, CR, 97, and *Metrologia*, 1984, **20**, 25) that specified the current definition, as follows:

> **The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.**

It follows that the speed of light in vacuum is exactly 299 792 458 meters per second, $c_0 = 299\ 792\ 458$ m/s.

The symbol c_0 (or sometimes simply c) is the conventional symbol for the speed of light in vacuum.

The original international prototype of the meter, which was sanctioned by the 1st CGPM in 1889 (CR, 34-38), is still kept at the BIPM under conditions specified in 1889.

2.1.1.2 Unit of mass (kilogram)

The international prototype of the kilogram, an artifact made of platinum-iridium, is kept at the BIPM under the conditions specified by the 1st CGPM in 1889 (CR, 34-38) when it sanctioned the prototype and declared:

> This prototype shall henceforth be considered to be the unit of mass.

The 3rd CGPM (1901, CR, 70), in a declaration intended to end the ambiguity in popular usage concerning the use of the word "weight," confirmed that:

> **The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.**

The complete declaration appears on p. 52.

It follows that the mass of the international prototype of the kilogram is always 1 kilogram exactly, $m(\mathcal{K}) = 1$ kg. However, due to the inevitable accumulation of contaminants on surfaces, the international prototype is subject to reversible surface contamination that approaches 1 μg per year in mass. For this reason, the CIPM declared that, pending further research, the reference mass of the international prototype is that immediately after cleaning and washing by a specified method (PV, 1989, **57**, 104-105 and PV, 1990, **58**, 95-97). The reference mass thus defined is used to calibrate national standards of platinum-iridium alloy (*Metrologia*, 1994, **31**, 317-336).

The symbol $m(\mathcal{K})$ is used to denote the mass of the international prototype of the kilogram, $\mathcal{K}$.

2.1.1.3 Unit of time (second)

The unit of time, the second, was at one time considered to be the fraction 1/86 400 of the mean solar day. The exact definition of "mean solar day" was left to the astronomers. However measurements showed that irregularities in the rotation of the Earth made this an unsatisfactory definition. In order to define the unit of time more precisely, the 11th CGPM (1960, Resolution 9; CR, 86) adopted a definition given by the International Astronomical Union based on the tropical year 1900. Experimental work, however, had already shown that an atomic standard of time, based on a transition between two energy levels of an atom or a molecule, could be realized and reproduced much more accurately. Considering that a very precise definition of the unit of time is indispensable for science and technology, the 13th CGPM (1967/68, Resolution 1; CR, 103 and *Metrologia*, 1968, **4**, 43) replaced the definition of the second by the following:

> **The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.**

It follows that the hyperfine splitting in the ground state of the cesium 133 atom is exactly 9 192 631 770 hertz, $\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}} = 9\,192\,631\,770$ Hz.

The symbol $\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$ is used to denote the frequency of the hyperfine transition in the ground state of the cesium atom.

At its 1997 meeting the CIPM affirmed that:

> This definition refers to a cesium atom at rest at a temperature of 0 K.

This note was intended to make it clear that the definition of the SI second is based on a cesium atom unperturbed by black body radiation, that is, in an environment whose thermodynamic temperature is 0 K. The frequencies of all primary frequency standards should therefore be corrected for the shift due to ambient radiation, as stated at the meeting of the Consultative Committee for Time and Frequency in 1999.

2.1.1.4 Unit of electric current (ampere)

Electric units, called "international units," for current and resistance, were introduced by the International Electrical Congress held in Chicago in 1893, and definitions of the "international ampere" and "international ohm" were confirmed by the International Conference in London in 1908.

Although it was already obvious on the occasion of the 8th CGPM (1933) that there was a unanimous desire to replace those "international units" by so-called "absolute units," the official decision to abolish them was only taken by the 9th CGPM (1948), which adopted the ampere for the unit of electric current, following a definition proposed by the CIPM (1946, Resolution 2; PV, **20**, 129-137):

> **The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2 × 10^{-7} newton per meter of length.**

It follows that the magnetic constant μ_0, also known as the permeability of vacuum, is exactly $4\pi \times 10^{-7}$ henries per meter, $\mu_0 = 4\pi \times 10^{-7}$ H/m.

The expression "MKS unit of force" which occurs in the original text of 1946 has been replaced here by "newton," a name adopted for this unit by the 9th CGPM (1948, Resolution 7; CR, 70).

2.1.1.5 Unit of thermodynamic temperature (kelvin)

The definition of the unit of thermodynamic temperature was given in substance by the 10th CGPM (1954, Resolution 3; CR, 79) which selected the triple point of water as the fundamental fixed point and assigned to it the temperature 273.16 K, so defining the unit. The 13th CGPM (1967/68, Resolution 3; CR, 104 and *Metrologia*, 1968, **4**, 43) adopted the name kelvin, symbol K, instead of "degree Kelvin," symbol °K, and defined the unit of thermodynamic temperature as follows (1967/68, Resolution 4; CR, 104 and *Metrologia*, 1968, **4**, 43):

> **The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.**

It follows that the thermodynamic temperature of the triple point of water is exactly 273.16 kelvins, $T_{\mathrm{TPW}} = 273.16$ K.

The symbol T_{TPW} is used to denote the thermodynamic temperature of the triple point of water.

At its 2005 meeting the CIPM affirmed that:

> This definition refers to water having the isotopic composition defined exactly by the following amount of substance ratios: 0.000 155 76 mole of ^{2}H per mole of ^{1}H, 0.000 379 9 mole of ^{17}O per mole of ^{16}O, and 0.002 005 2 mole of ^{18}O per mole of ^{16}O.

Because of the manner in which temperature scales used to be defined, it remains common practice to express a thermodynamic temperature, symbol T, in terms of its difference from the reference temperature $T_0 = 273.15$ K, the ice point. This difference is called the Celsius temperature, symbol t, which is defined by the quantity equation:

$$T = T - T_0.$$

The unit of Celsius temperature is the degree Celsius, symbol °C, which is by definition equal in magnitude to the kelvin. A difference or interval of temperature may be expressed in kelvins or in degrees Celsius (13th CGPM, 1967/68, Resolution 3, mentioned above), the numerical value of the temperature difference being the same. However, the numerical value of a Celsius temperature expressed in degrees Celsius is related to the numerical value of the thermodynamic temperature expressed in kelvins by the relation

$$t/°\mathrm{C} = T/\mathrm{K} - 273.15.$$

The kelvin and the degree Celsius are also units of the International Temperature Scale of 1990 (ITS-90) adopted by the CIPM in 1989 in its Recommendation 5 (CI-1989; PV, **57**, 115 and *Metrologia*, 1990, **27**, 13).

2.1.1.6 Unit of amount of substance (mole)

Following the discovery of the fundamental laws of chemistry, units called, for example, "gram-atom" and "gram-molecule," were used to specify amounts of chemical elements or compounds. These units had a direct connection with "atomic weights" and "molecular weights," which are in fact relative masses. "Atomic weights" were originally referred to the atomic weight of oxygen, by general agreement taken as 16. But whereas physicists separated the isotopes in a mass spectrometer and attributed the value 16 to one of the isotopes of oxygen, chemists attributed the same value to the (slightly variable) mixture of isotopes 16, 17 and 18, which was for them the naturally occurring element oxygen. Finally an agreement between the International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) brought this duality to an end in 1959/60. Physicists and chemists have ever since agreed to assign the value 12, exactly, to the so-called atomic weight of the isotope of carbon with mass number 12 (carbon 12, ^{12}C), correctly called the relative atomic mass $A_r(^{12}\mathrm{C})$. The unified scale thus obtained gives the relative atomic and molecular masses, also known as the atomic and molecular weights, respectively.

The recommended symbol for relative atomic mass (atomic weight) is $A_r(X)$, where the atomic entity X should be specified, and for relative molecular mass of a molecule (molecular weight) it is $M_r(X)$, where the molecular entity X should be specified.

The quantity used by chemists to specify the amount of chemical elements or compounds is now called "amount of substance." Amount of substance is defined to be proportional to the number of specified elementary entities in a sample, the proportionality constant being a universal constant which is the same for all samples. The unit of amount of substance is called the *mole*, symbol mol, and the mole is defined by specifying the mass of carbon 12 that constitutes one mole of carbon 12 atoms. By international agreement this was fixed at 0.012 kg, i.e. 12 g.

Following proposals by the IUPAP, the IUPAC, and the ISO, the CIPM gave a definition of the mole in 1967 and confirmed it in 1969. This was adopted by the 14th CGPM (1971, Resolution 3; CR, 78 and *Metrologia*, 1972, **8**, 36):

1. **The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is "mol."**
2. **When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.**

The molar mass of an atom or molecule X is denoted $M(X)$ or M_X, and is the mass per mole of X.

It follows that the molar mass of carbon 12 is exactly 12 grams per mole, $M(^{12}\mathrm{C}) = 12$ g/mol.

In 1980 the CIPM approved the report of the CCU (1980) which specified that

> In this definition, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to.

When the definition of the mole is quoted, it is conventional also to include this remark.

The definition of the mole also determines the value of the universal constant that relates the number of entities to amount of substance for any sample. This constant is called the Avogadro constant, symbol N_A or L. If $N(X)$ denotes the number of entities X in a specified sample, and if $n(X)$ denotes the amount of substance of entities X in the same sample, the relation is

$$n(X) = N(X)/N_A.$$

Note that since $N(X)$ is dimensionless, and $n(X)$ has the SI unit mole, the Avogadro constant has the coherent SI unit reciprocal mole.

In the name "amount of substance," the words "of substance" could for simplicity be replaced by words to specify the substance concerned in any particular application, so that one may, for example, talk of "amount of hydrogen chloride, HCl," or "amount of benzene, C_6H_6." It is important to always give a precise specification of the entity involved (as emphasized in the second sentence of the definition of the mole); this should preferably be done by giving the empirical chemical formula of the material involved. Although the word "amount" has a more general dictionary definition, this abbreviation of the full name "amount of substance" may be used for brevity. This also applies to derived quantities such as "amount of substance concentration," which may simply be called "amount concentration." However, in the field of clinical chemistry the name "amount of substance concentration" is generally abbreviated to "substance concentration."

2.1.1.7 Unit of luminous intensity (candela)

The units of luminous intensity based on flame or incandescent filament standards in use in various countries before 1948 were replaced initially by the "new candle" based on the luminance of a Planck radiator (a black body) at the temperature of freezing platinum. This modification had been prepared by the International Commission on Illumination (CIE) and by the CIPM before 1937, and the decision was promulgated by the CIPM in 1946. It was then ratified in 1948 by the 9th CGPM which adopted a new international name for this unit, the *candela*, symbol cd; in 1967 the 13th CGPM (Resolution 5, CR, 104 and *Metrologia*, 1968, **4**, 43-44) gave an amended version of this definition.

In 1979, because of the difficulties in realizing a Planck radiator at high temperatures, and the new possibilities offered by radiometry, i.e. the measurement of optical radiation power, the 16th CGPM (1979, Resolution 3; CR, 100 and *Metrologia*, 1980, **16**, 56) adopted a new definition of the candela:

> **The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.**

It follows that the spectral luminous efficacy for monochromatic radiation of frequency of 540×10^{12} hertz is exactly 683 lumens per watt, $K(\lambda_{555}) = 683$ lm/W $= 683$ cd sr/W (the wavelength λ of radiation of this frequency is about 555 nm).

2.1.2 Symbols for the seven base units

The base units of the International System are listed in Table 1, which relates the base quantity to the unit name and unit symbol for each of the seven base units (10th CGPM (1954, Resolution 6; CR, 80); 11th CGPM (1960, Resolution 12; CR, 87); 13th CGPM (1967/68, Resolution 3; CR, 104 and *Metrologia*, 1968, **4**, 43); 14th CGPM (1971, Resolution 3; CR, 78 and *Metrologia*, 1972, **8**, 36)).

Table 1. SI base units

Base quantity		SI base unit	
Name	Symbol	Name	Symbol
length	*l, x, r*, etc.	meter	m
mass	*m*	kilogram	kg
time, duration	*t*	second	s
electric current	*I, i*	ampere	A
thermodynamic temperature	*T*	kelvin	K
amount of substance	*n*	mole	mol
luminous intensity	I_v	candela	cd

The symbols for quantities are generally single letters of the Latin or Greek alphabets, printed in an italic font, and are *recommendations*.

The symbols for units are *mandatory*, see chapter 5.

2.2 SI derived units

Derived units are products of powers of base units. Coherent derived units are products of powers of base units that include no numerical factor other than 1. The base and coherent derived units of the SI form a coherent set, designated the set of *coherent SI units* (see 1.4, p. 12).

2.2.1 Derived units expressed in terms of base units

The number of quantities in science is without limit, and it is not possible to provide a complete list of derived quantities and derived units. However, Table 2 lists some examples of derived quantities, and the corresponding coherent derived units expressed directly in terms of base units.

Table 2. Examples of coherent derived units in the SI expressed in terms of base units

Derived quantity		SI coherent derived unit	
Name	Symbol	Name	Symbol
area	A	square meter	m^2
volume	V	cubic meter	m^3
speed, velocity	v	meter per second	m/s
acceleration	a	meter per second squared	m/s^2
wavenumber	σ, $\tilde{\nu}$	reciprocal meter	m^{-1}
density, mass density	ρ	kilogram per cubic meter	kg/m^3
surface density	ρ_A	kilogram per square meter	kg/m^2
specific volume	v	cubic meter per kilogram	m^3/kg
current density	j	ampere per square meter	A/m^2
magnetic field strength	H	ampere per meter	A/m
amount concentration [(a)], concentration	c	mole per cubic meter	mol/m^3
mass concentration	ρ, γ	kilogram per cubic meter	kg/m^3
luminance	L_v	candela per square meter	cd/m^2
refractive index [(b)]	n	one	1
relative permeability [(b)]	μ_r	one	1

(*a*) In the field of clinical chemistry this quantity is also called "substance concentration."

(*b*) These are dimensionless quantities, or quantities of dimension one, and the symbol "1" for the unit (the number "one") is generally omitted in specifying the values of dimensionless quantities.

2.2.2 Units with special names and symbols; units that incorporate special names and symbols

For convenience, certain coherent derived units have been given special names and symbols. There are 22 such units, as listed in Table 3. These special names and symbols may themselves be used in combination with the names and symbols for base units and for other derived units to express the units of other derived quantities. Some examples are given in Table 4. The special names and symbols are simply a compact form for the expression of combinations of base units that are used frequently, but in many cases they also serve to remind the reader of the quantity involved. The SI prefixes may be used with any of the special names and symbols, but when this is done the resulting unit will no longer be coherent.

Among these names and symbols the last four entries in Table 3 are of particular note since they were adopted by the 15th CGPM (1975, Resolutions 8 and 9; CR, 105 and *Metrologia*, 1975, **11**, 180), the 16th CGPM (1979, Resolution 5; CR, 100 and *Metrologia*, 1980, **16**, 56) and the 21st CGPM (1999, Resolution 12; CR, 334-335 and *Metrologia*, 2000, **37**, 95) specifically with a view to safeguarding human health.

In both Tables 3 and 4 the final column shows how the SI units concerned may be expressed in terms of SI base units. In this column factors such as m^0, kg^0, etc., which are all equal to 1, are not shown explicitly.

Table 3. Coherent derived units in the SI with special names and symbols

	SI coherent derived unit [(a)]			
Derived quantity	Name	Symbol	Expressed in terms of other SI units	Expressed in terms of SI base units
plane angle	radian [(b)]	rad	1 [(b)]	m/m
solid angle	steradian [(b)]	sr [(c)]	1 [(b)]	m^2/m^2
frequency	hertz [(d)]	Hz		s^{-1}
force	newton	N		$m\ kg\ s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
energy, work, amount of heat	joule	J	N m	$m^2\ kg\ s^{-2}$
power, radiant flux	watt	W	J/s	$m^2\ kg\ s^{-3}$
electric charge, amount of electricity	coulomb	C		s A
electric potential difference [(e)], electromotive force	volt	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
capacitance	farad	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
electric resistance	ohm	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
electric conductance	siemens	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
magnetic flux	weber	Wb	V s	$m^2\ kg\ s^{-2}\ A^{-1}$
magnetic flux density	tesla	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
inductance	henry	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
Celsius temperature	degree Celsius [(f)]	°C		K
luminous flux	lumen	lm	cd sr [(c)]	cd
illuminance	lux	lx	lm/m^2	m^{-2} cd
activity referred to a radionuclide [(g)]	becquerel [(d)]	Bq		s^{-1}
absorbed dose, specific energy (imparted), kerma	gray	Gy	J/kg	$m^2\ s^{-2}$
dose equivalent, ambient dose equivalent, directional dose equivalent, personal dose equivalent	sievert [(h)]	Sv	J/kg	$m^2\ s^{-2}$
catalytic activity	katal	kat		s^{-1} mol

(*a*) The SI prefixes may be used with any of the special names and symbols, but when this is done the resulting unit will no longer be coherent.

(*b*) The radian and steradian are special names for the number one that may be used to convey information about the quantity concerned. In practice the symbols rad and sr are used where appropriate, but the symbol for the derived unit one is generally omitted in specifying the values of dimensionless quantities.

(*c*) In photometry the name steradian and the symbol sr are usually retained in expressions for units.

(*d*) The hertz is used only for periodic phenomena, and the becquerel is used only for stochastic processes in activity referred to a radionuclide.

(*e*) **Editors' note:** Electric potential difference is also called "voltage" in the United States and in many other countries, as well as "electric tension" or simply "tension" in some countries.

(*f*) The degree Celsius is the special name for the kelvin used to express Celsius temperatures. The degree Celsius and the kelvin are equal in size, so that the numerical value of a temperature difference or temperature interval is the same when expressed in either degrees Celsius or in kelvins.

(*g*) Activity referred to a radionuclide is sometimes incorrectly called radioactivity.

(*h*) See CIPM Recommendation 2 (CI-2002), p. 78, on the use of the sievert (PV, 2002, 70, 205).

Table 4. Examples of SI coherent derived units whose names and symbols include SI coherent derived units with special names and symbols

	SI coherent derived unit		
Derived quantity	Name	Symbol	Expressed in terms of SI base units
dynamic viscosity	pascal second	Pa s	m^{-1} kg s^{-1}
moment of force	newton meter	N m	m^2 kg s^{-2}
surface tension	newton per meter	N/m	kg s^{-2}
angular velocity	radian per second	rad/s	m m^{-1} s^{-1} = s^{-1}
angular acceleration	radian per second squared	rad/s^2	m m^{-1} s^{-2} = s^{-2}
heat flux density, irradiance	watt per square meter	W/m^2	kg s^{-3}
heat capacity, entropy	joule per kelvin	J/K	m^2 kg s^{-2} K^{-1}
specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg K)	m^2 s^{-2} K^{-1}
specific energy	joule per kilogram	J/kg	m^2 s^{-2}
thermal conductivity	watt per meter kelvin	W/(m K)	m kg s^{-3} K^{-1}
energy density	joule per cubic meter	J/m^3	m^{-1} kg s^{-2}
electric field strength	volt per meter	V/m	m kg s^{-3} A^{-1}
electric charge density	coulomb per cubic meter	C/m^3	m^{-3} s A
surface charge density	coulomb per square meter	C/m^2	m^{-2} s A
electric flux density, electric displacement	coulomb per square meter	C/m^2	m^{-2} s A
permittivity	farad per meter	F/m	m^{-3} kg^{-1} s^4 A^2
permeability	henry per meter	H/m	m kg s^{-2} A^{-2}
molar energy	joule per mole	J/mol	m^2 kg s^{-2} mol^{-1}
molar entropy, molar heat capacity	joule per mole kelvin	J/(mol K)	m^2 kg s^{-2} K^{-1} mol^{-1}
exposure (x and γ rays)	coulomb per kilogram	C/kg	kg^{-1} s A
absorbed dose rate	gray per second	Gy/s	m^2 s^{-3}
radiant intensity	watt per steradian	W/sr	m^4 m^{-2} kg s^{-3} = m^2 kg s^{-3}
radiance	watt per square meter steradian	W/(m^2 sr)	m^2 m^{-2} kg s^{-3} = kg s^{-3}
catalytic activity concentration	katal per cubic meter	kat/m^3	m^{-3} s^{-1} mol

The values of several different quantities may be expressed using the same name and symbol for the SI unit. Thus for the quantity heat capacity as well as the quantity entropy, the SI unit is the joule per kelvin. Similarly for the base quantity electric current as well as the derived quantity magnetomotive force, the SI unit is the ampere. It is therefore important not to use the unit alone to specify the quantity.

This applies not only to scientific and technical texts, but also, for example, to measuring instruments (i.e. an instrument read-out should indicate both the unit and the quantity measured).

A derived unit can often be expressed in different ways by combining base units with derived units having special names. Joule, for example, may formally be written newton meter, or kilogram meter squared per second squared. This, however, is an algebraic freedom to be governed by common sense physical considerations; in a given situation some forms may be more helpful than others.

In practice, with certain quantities, preference is given to the use of certain special unit names, or combinations of unit names, to facilitate the distinction between different quantities having the same dimension. When using this freedom, one may recall the process by which the quantity is defined. For example, the quantity torque may be thought of as the cross product of force and distance, suggesting the unit newton meter, or it may be thought of as energy per angle, suggesting the unit joule per radian. The SI unit of frequency is given as the hertz, implying the unit cycles per second; the SI unit of angular velocity is given as the radian per second; and the SI unit of activity is designated the becquerel, implying the unit counts per second. Although it would be formally correct to write all three of these units as the reciprocal second, the use of the different names emphasises the different nature of the quantities concerned. Using the unit radian per second for angular velocity, and hertz for frequency, also emphasizes that the numerical value of the angular velocity in radian per second is 2π times the numerical value of the corresponding frequency in hertz.

In the field of ionizing radiation, the SI unit of activity is designated the becquerel rather than the reciprocal second, and the SI units of absorbed dose and dose equivalent are designated the gray and the sievert, respectively, rather than the joule per kilogram. The special names becquerel, gray, and sievert were specifically introduced because of the dangers to human health that might arise from mistakes involving the units reciprocal second and joule per kilogram, in case the latter units were incorrectly taken to identify the different quantities involved.

The CIPM, recognizing the particular importance of the health-related units, adopted a detailed text on the sievert for the 5th edition of this Brochure: Recommendation 1 (CI-1984), adopted by the CIPM (PV, 1984, **52**, 31 and *Metrologia*, 1985, **21**, 90), and Recommendation 2 (CI-2002), adopted by the CIPM (PV, **70**, 205), see pp. 71 and 78, respectively.

2.2.3 Units for dimensionless quantities, also called quantities of dimension one

Certain quantities are defined as the ratio of two quantities of the same kind, and are thus dimensionless, or have a dimension that may be expressed by the number one. The coherent SI unit of all such dimensionless quantities, or quantities of dimension one, is the number one, since the unit must be the ratio of two identical SI units. The values of all such quantities are simply expressed as numbers, and the unit one is not explicitly shown. Examples of such quantities are refractive index, relative permeability, and friction factor. There are also some quantities that are defined as a more complex product of simpler quantities in such a way that the product is dimensionless. Examples include the "characteristic numbers" like the Reynolds number $Re = \rho v l/\eta$, where ρ is mass density, η is dynamic viscosity, v is speed, and l

is length. For all these cases the unit may be considered as the number one, which is a dimensionless derived unit.

Another class of dimensionless quantities are numbers that represent a count, such as a number of molecules, degeneracy (number of energy levels), and partition function in statistical thermodynamics (number of thermally accessible states). All of these counting quantities are also described as being dimensionless, or of dimension one, and are taken to have the SI unit one, although the unit of counting quantities cannot be described as a derived unit expressed in terms of the base units of the SI. For such quantities, the unit one may instead be regarded as a further base unit.

In a few cases, however, a special name is given to the unit one, in order to facilitate the identification of the quantity involved. This is the case for the radian and the steradian. The radian and steradian have been identified by the CGPM as special names for the coherent derived unit one, to be used to express values of plane angle and solid angle, respectively, and are therefore included in Table 3.

3 Decimal multiples and submultiples of SI units

3.1 SI prefixes

The 11th CGPM (1960, Resolution 12; CR, 87) adopted a series of prefix names and prefix symbols to form the names and symbols of the decimal multiples and submultiples of SI units, ranging from 10^{12} to 10^{-12}. Prefixes for 10^{-15} and 10^{-18} were added by the 12th CGPM (1964, Resolution 8; CR, 94), for 10^{15} and 10^{18} by the 15th CGPM (1975, Resolution 10; CR, 106 and *Metrologia*, 1975, **11**, 180-181), and for 10^{21}, 10^{24}, 10^{-21} and 10^{-24} by the 19th CGPM (1991, Resolution 4; CR, 185 and *Metrologia*, 1992, **29**, 3). Table 5 lists all approved prefix names and symbols.

These SI prefixes refer strictly to powers of 10. They should not be used to indicate powers of 2 (for example, one kilobit represents 1000 bits and not 1024 bits). The IEC has adopted prefixes for binary powers in the international standard IEC 60027-2: 2005, third edition, *Letter symbols to be used in electrical technology – Part 2: Telecommunications and electronics*. The names and symbols for the prefixes corresponding to 2^{10}, 2^{20}, 2^{30}, 2^{40}, 2^{50}, and 2^{60} are, respectively: kibi, Ki; mebi, Mi; gibi, Gi; tebi, Ti; pebi, Pi; and exbi, Ei. Thus, for example, one kibibyte would be written: 1 KiB = 2^{10} B = 1024 B, where B denotes a byte. Although these prefixes are not part of the SI, they should be used in the field of information technology to avoid the incorrect usage of the SI prefixes.

Table 5. SI prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10^{1}	deka	da	10^{-1}	deci	d
10^{2}	hecto	h	10^{-2}	centi	c
10^{3}	kilo	k	10^{-3}	milli	m
10^{6}	mega	M	10^{-6}	micro	µ
10^{9}	giga	G	10^{-9}	nano	n
10^{12}	tera	T	10^{-12}	pico	p
10^{15}	peta	P	10^{-15}	femto	f
10^{18}	exa	E	10^{-18}	atto	a
10^{21}	zetta	Z	10^{-21}	zepto	z
10^{24}	yotta	Y	10^{-24}	yocto	y

Prefix symbols are printed in roman (upright) type, as are unit symbols, regardless of the type used in the surrounding text, and are attached to unit symbols without a space between the prefix symbol and the unit symbol. With the exception of da (deka), h (hecto), and k (kilo), all multiple prefix symbols are capital (upper case) letters, and all submultiple prefix symbols are lower case letters. All prefix names are printed in lower case letters, except at the beginning of a sentence.

Examples of the use of prefixes:
pm (picometer)
mmol (millimole)
GΩ (gigaohm)
THz (terahertz)

The grouping formed by a prefix symbol attached to a unit symbol constitutes a new inseparable unit symbol (forming a multiple or submultiple of the unit concerned) that can be raised to a positive or negative power and that can be combined with other unit symbols to form compound unit symbols.

Examples:

$$2.3 \text{ cm}^3 = 2.3 \text{ (cm)}^3 = 2.3 \text{ } (10^{-2} \text{ m})^3 = 2.3 \times 10^{-6} \text{ m}^3$$

$$1 \text{ cm}^{-1} = 1 \text{ (cm)}^{-1} = 1 \text{ } (10^{-2} \text{ m})^{-1} = 10^2 \text{ m}^{-1} = 100 \text{ m}^{-1}$$

$$1 \text{ V/cm} = (1 \text{ V})/(10^{-2} \text{ m}) = 10^2 \text{ V/m} = 100 \text{ V/m}$$

$$5000 \text{ µs}^{-1} = 5000 \text{ (µs)}^{-1} = 5000 \text{ } (10^{-6} \text{ s})^{-1} = 5 \times 10^9 \text{ s}^{-1}$$

Similarly prefix names are also inseparable from the unit names to which they are attached. Thus, for example, millimeter, micropascal, and meganewton are single words.

Compound prefix symbols, that is, prefix symbols formed by the juxtaposition of two or more prefix symbols, are not permitted. This rule also applies to compound prefix names.

nm (nanometer), ***but not*** mµm (millimicrometer)

Prefix symbols can neither stand alone nor be attached to the number 1, the symbol for the unit one. Similarly, prefix names cannot be attached to the name of the unit one, that is, to the word "one."

The number of lead atoms in the sample is $N(\text{Pb}) = 5 \times 10^6$, ***but not*** $N(\text{Pb}) = 5$ M, where M is intended to be the prefix mega standing on its own.

Prefix names and symbols are used with a number of non-SI units (see Chapter 5), but they are never used with the units of time: minute, min; hour, h; day, d. However astronomers use milliarcsecond, which they denote by the symbol mas, and microarcsecond, which they denote by the symbol µas, and they use both as units for measuring very small angles.†

3.2 The kilogram

Among the base units of the International System, the kilogram is the only one whose name and symbol, for historical reasons, include a prefix. Names and symbols for decimal multiples and submultiples of the unit of mass are formed by attaching prefix names to the unit name "gram," and prefix symbols to the unit symbol "g" (CIPM 1967, Recommendation 2; PV, **35**, 29 and *Metrologia*, 1968, **4**, 45).

10^{-6} kg = 1 mg, ***but not*** 1 µkg (microkilogram)

† Editors' note: This last sentence has been slightly modified for clarity.

4 Units outside the SI

The International System of Units, the SI, is a system of units, adopted by the CGPM, which provides the internationally agreed reference in terms of which all other units are now defined. It is recommended for use throughout science, technology, engineering, and commerce. The SI base units, and the SI coherent derived units, including those with special names, have the important advantage of forming a coherent set, with the effect that unit conversions are not required when inserting particular values for quantities into quantity equations. Because the SI is the only system of units that is globally recognized, it also has a clear advantage for establishing a worldwide dialogue. Finally, it simplifies the teaching of science and technology to the next generation if everyone uses this system.

Nonetheless it is recognized that some non-SI units still appear in the scientific, technical, and commercial literature, and will continue to be used for many years. Some non-SI units are of historical importance in the established literature. Other non-SI units, such as the units of time and angle, are so deeply embedded in the history and culture of the human race that they will continue to be used for the foreseeable future. Individual scientists should also have the freedom to sometimes use non-SI units for which they see a particular scientific advantage in their work. An example of this is the use of CGS-Gaussian units in electromagnetic theory applied to quantum electrodynamics and relativity. For these reasons it is helpful to list some of the more important non-SI units, as is done below. However, if these units are used it should be understood that the advantages of the SI are lost.

The inclusion of non-SI units in this text does not imply that the use of non-SI units is to be encouraged. For the reasons already stated SI units are generally to be preferred. It is also desirable to avoid combining non-SI units with units of the SI; in particular, the combination of non-SI units with the SI to form compound units should be restricted to special cases in order not to compromise the advantages of the SI. Finally, when any of the non-SI units in Tables 7, 8, and 9 are used, it is good practice to define the non-SI unit in terms of the corresponding SI unit.

4.1 Non-SI units accepted for use with the SI, and units based on fundamental constants

The CIPM (2004) has revised the classification of non-SI units from that in the previous (7th) edition of this Brochure. Table 6 gives non-SI units that are accepted for use with the International System by the CIPM, because they are widely used with the SI in matters of everyday life. Their use is expected to continue indefinitely, and each has an exact definition in terms of an SI unit. Tables 7, 8 and 9 contain units that are used only in special circumstances. The units in Table 7 are related to fundamental constants, and their values have to be determined experimentally. Tables 8 and 9 contain units that have exactly defined values in terms of SI units, and are used in particular circumstances to satisfy the needs of commercial, legal, or specialized scientific interests. It is likely that these units will continue to be used for many years. Many of these units are also important for the interpretation of older scientific texts. Each of the Tables 6, 7, 8 and 9 is discussed in turn below.

Table 6 includes the traditional units of time and angle. It also contains the hectare, the liter, and the metric ton (or tonne), which are all in common everyday use throughout the world, and which differ from the corresponding coherent SI unit by an integer power of ten. The SI prefixes are used with several of these units, but not with the units of time.

Table 6. Non-SI units accepted for use with the International System of Units

Quantity	Name of unit	Symbol for unit	Value in SI units
time	minute	min	1 min = 60 s
	hour [(a)]	h	1 h = 60 min = 3600 s
	day	d	1 d = 24 h = 86 400 s
plane angle	degree [(b, c)]	°	$1° = (\pi/180)$ rad
	minute	′	$1' = (1/60)° = (\pi/10\,800)$ rad
	second [(d)]	″	$1'' = (1/60)' = (\pi/648\,000)$ rad
area	hectare [(e)]	ha	$1 \text{ ha} = 1 \text{ hm}^2 = 10^4 \text{ m}^2$
volume	liter [(f)]	L	$1 \text{ L} = 1 \text{ dm}^3 = 10^3 \text{ cm}^3 = 10^{-3} \text{ m}^3$
mass	metric ton [(g)]	t	$1 \text{ t} = 10^3 \text{ kg}$

(*a*) The symbol for this unit is included in Resolution 7 of the 9th CGPM (1948; CR, 70).

(*b*) ISO 31 recommends that the degree be divided decimally rather than using the minute and the second. For navigation and surveying, however, the minute has the advantage that one minute of latitude on the surface of the Earth corresponds (approximately) to one nautical mile.

(*c*) The gon (or grad, where grad is an alternative name for the gon) is an alternative unit of plane angle to the degree, defined as (π/200) rad. Thus there are 100 gon in a right angle. The potential value of the gon in navigation is that because the distance from the pole to the equator of the Earth is approximately 10 000 km, 1 km on the surface of the Earth subtends an angle of one centigon at the center of the Earth. However the gon is rarely used.

(*d*) For applications in astronomy, small angles are measured in arcseconds (i.e. seconds of plane angle), denoted by the symbol as or by the symbol ″, milliarcseconds, microarcseconds, and picoarcseconds, denoted by the symbols mas, μas, and pas, respectively, where arcsecond is an alternative name for second of plane angle.

(*e*) The unit hectare, and its symbol ha, were adopted by the CIPM in 1879 (PV, 1879, 41). The hectare is used to express land area.

(*f*) The liter, and the symbol lower-case l, were adopted by the CIPM in 1879 (PV, 1879, 41). The alternative symbol, capital L, was adopted by the 16th CGPM (1979, Resolution 6; CR, 101 and *Metrologia,* 1980, **16**, 56-57) in order to avoid the risk of confusion between the letter l (el) and the numeral 1 (one). **Editors' note:** Since the preferred unit symbol for the liter in the United States is L, only L is given in the table; see the *Federal Register* notice of July 28, 1998, "Metric System of Measurement: Interpretation of the International System of Units for the United States" (FR 40334-4030).

(*g*) **Editors' note:** Metric ton is the name to be used for this unit in the United States; see the aforementioned *Federal Register* notice. The original English text in the BIPM SI Brochure uses the CGPM adopted name "tonne" and footnote (g) reads as follows: The tonne, and its symbol t, were adopted by the CIPM in 1879 (PV, 1879, 41). In English speaking countries this unit is usually called "metric ton."

Table 7 contains units whose values in SI units have to be determined experimentally, and thus have an associated uncertainty. Except for the astronomical unit, all other units in Table 7 are related to fundamental physical constants. The first four units, the non-SI units electronvolt, symbol eV, dalton or unified atomic mass unit, symbol Da or u, respectively, and the astronomical unit, symbol ua, have been accepted for use with the SI by the CIPM. The units in Table 7 play important roles in a number of specialized fields in which the results of measurements or calculations are most conveniently and usefully expressed in these units. For the electronvolt and the dalton the values depend on the elementary charge e and the Avogadro constant N_A, respectively.

There are many other units of this kind, because there are many fields in which it is most convenient to express the results of experimental observations or of theoretical calculations in terms of fundamental constants of nature. The two most important of such unit systems based on fundamental constants are the natural unit (n.u.) system used in high energy or particle physics, and the atomic unit (a.u.) system used in atomic physics and quantum chemistry. In the n.u. system, the base quantities for mechanics are speed, action, and mass, for which the base units are the speed of light in vacuum c_0, the Planck constant h divided by 2π, called the reduced Planck constant with symbol $\hbar$, and the mass of the electron m_e, respectively. In general these units are not given any special names or symbols but are simply called the n.u. of speed, symbol c_0, the n.u. of action, symbol $\hbar$, and the n.u. of mass, symbol m_e. In this system, time is a derived quantity and the n.u. of time is a derived unit equal to the combination of base units $\hbar/m_e c_0^2$. Similarly, in the a.u. system, any four of the five quantities charge, mass, action, length, and energy are taken as base quantities. The corresponding base units are the elementary charge e, electron mass m_e, action $\hbar$, Bohr radius (or bohr) a_0, and Hartree energy (or hartree) E_h, respectively. In this system, time is again a derived quantity and the a.u. of time a derived unit, equal to the combination of units $\hbar/E_h$. Note that $a_0 = \alpha/(4\pi R_\infty)$, where α is the fine-structure constant and R_∞ is the Rydberg constant; and $E_h = e^2/(4\pi\varepsilon_0 a_0) = 2R_\infty hc_0 = \alpha^2 m_e c_0^2$, where ε_0 is the electric constant and has an exact value in the SI.

For information, these ten natural and atomic units and their values in SI units are also listed in Table 7. Because the quantity systems on which these units are based differ so fundamentally from that on which the SI is based, they are not generally used with the SI, and the CIPM has not formally accepted them for use with the International System. To ensure understanding, the final result of a measurement or calculation expressed in natural or atomic units should also always be expressed in the corresponding SI unit. Natural units (n.u.) and atomic units (a.u.) are used only in their own special fields of particle physics, and atomic physics and quantum chemistry, respectively. Standard uncertainties in the least significant digits are shown in parenthesis after each numerical value.

Table 7. Non-SI units whose values in SI units must be obtained experimentally†

Quantity	Name of unit	Symbol for unit	Value in SI units [(a)]
	Units accepted for use with the SI		
energy	electronvolt [(b)]	eV	1 eV = 1.602 176 53(14) × 10^{-19} J
mass	dalton, [(c)]	Da	1 Da = 1.660 538 86(28) × 10^{-27} kg
	unified atomic mass unit	u	1 u = 1 Da
length	astronomical unit [(d)]	ua	1 ua = 1.495 978 706 91(6) × 10^{11} m
	Natural units (n.u.)		
speed	n.u. of speed (speed of light in vacuum)	c_0	299 792 458 m/s (exact)
action	n.u. of action (reduced Planck constant)	$\hbar$	1.054 571 68(18) × 10^{-34} J s
mass	n.u. of mass (electron mass)	m_e	9.109 3826(16) × 10^{-31} kg
time	n.u. of time	$\hbar/(m_e c_0^2)$	1.288 088 6677(86) × 10^{-21} s
	Atomic units (a.u.)		
charge	a.u. of charge (elementary charge)	e	1.602 176 53(14) × 10^{-19} C
mass	a.u. of mass (electron mass)	m_e	9.109 3826(16) × 10^{-31} kg
action	a.u. of action (reduced Planck constant)	$\hbar$	1.054 571 68(18) × 10^{-34} J s
length	a.u. of length, bohr (Bohr radius)	a_0	0.529 177 2108(18) × 10^{-10} m
energy	a.u. of energy, hartree (Hartree energy)	E_h	4.359 744 17(75) × 10^{-18} J
time	a.u. of time	$\hbar/E_h$	2.418 884 326 505(16) × 10^{-17} s

(*a*) The values in SI units of all units in this table, except the astronomical unit, are taken from the 2002 CODATA set of recommended values of the fundamental physical constants, P.J. Mohr and B.N. Taylor, *Rev. Mod. Phys.*, 2005, **77**, 1-107. The standard uncertainty in the last two digits is given in parenthesis (see 5.3.5, p. 43).

(*b*) The electronvolt is the kinetic energy acquired by an electron in passing through a potential difference of one volt in vacuum. The electronvolt is often combined with the SI prefixes.

(*c*) The dalton (Da) and the unified atomic mass unit (u) are alternative names (and symbols) for the same unit, equal to 1/12 times the mass of a free carbon 12 atom, at rest and in its ground state. The dalton is often combined with SI prefixes, for example to express the masses of large molecules in kilodaltons, kDa, or megadaltons, MDa, or to express the values of small mass differences of atoms or molecules in nanodaltons, nDa, or even picodaltons, pDa.

(*d*) The astronomical unit is approximately equal to the mean Earth-Sun distance. It is the radius of an unperturbed circular Newtonian orbit about the Sun of a particle having infinitesimal mass, moving with a mean motion of 0.017 202 098 95 radians per day (known as the Gaussian constant). The value given for the astronomical unit is quoted from the IERS Conventions 2003 (D.D. McCarthy and G. Petit eds., *IERS Technical Note* 32, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2004, 12). The value of the astronomical unit in meters comes from the JPL ephemerides DE403 (Standish E.M., Report of the IAU WGAS Sub-Group on Numerical Standards, *Highlights of Astronomy*, Appenzeller ed., Dordrecht: Kluwer Academic Publishers, 1995, 180-184).

† Editors' note: Only the units in Table 6, the first four units in Table 7, and the neper, bel, and decibel in Table 8 have been formally accepted for use with the SI by the CIPM.

Tables 8 and 9 contain non-SI units that are used by special interest groups for a variety of different reasons. Although the use of SI units is to be preferred for reasons already emphasized, authors who see a particular advantage in using these non-SI units should have the freedom to use the units that they consider to be best suited to their purpose. Since, however, SI units are the international meeting ground in terms of which all other units are defined, those who use units from Tables 8 and 9 should always give the definition of the units they use in terms of SI units.

Table 8 also gives the units of logarithmic ratio quantities, the neper, bel, and decibel. These are dimensionless units that are somewhat different in their nature from other dimensionless units, and some scientists consider that they should not even be called units. They are used to convey information on the nature of the logarithmic ratio quantity concerned. The neper, Np, is used to express the values of quantities whose numerical values are based on the use of the Napierian (or natural) logarithm, $\ln = \log_e$. The bel and the decibel, B and dB, where 1 dB = (1/10) B, are used to express the values of logarithmic ratio quantities whose numerical values are based on the decadic logarithm, $\lg = \log_{10}$. The way in which these units are interpreted is described in footnotes (*g*) and (*h*) of Table 8. The numerical values of these units are rarely required. The units neper, bel, and decibel have been accepted by the CIPM for use with the International System, but are not considered as SI units.

The SI prefixes are used with two of the units in Table 8, namely, with the bar (e.g. millibar, mbar), and with the bel, specifically for the decibel, dB. The decibel is listed explicitly in the table because the bel is rarely used without the prefix.

Table 8. Other non-SI units

Quantity	Name of unit	Symbol for unit	Value in SI units
pressure	bar [(a)]	bar	1 bar = 0.1 MPa = 100 kPa = 10^5 Pa
	millimeter of mercury [(b)]	mmHg	1 mmHg ≈ 133.322 Pa
length	ångström [(c)]	Å	1 Å = 0.1 nm = 100 pm = 10^{-10} m
distance	nautical mile [(d)]	M	1 M = 1852 m
area	barn [(e)]	b	1 b = 100 fm^2 = $(10^{-12}$ cm$)^2$ = 10^{-28} m^2
speed	knot [(f)]	kn	1 kn = (1852/3600) m/s
logarithmic ratio quantities	neper [(g, i)]	Np	[see footnote (*j*) regarding the
	bel [(h, i)]	B	numerical value of the neper, the
	decibel [(h, i)]	dB	bel, and the decibel]

(*a*) The bar and its symbol are included in Resolution 7 of the 9th CGPM (1948; CR, 70). Since 1982 one bar has been used as the standard pressure for tabulating all thermodynamic data. Prior to 1982 the standard pressure used to be the standard atmosphere, equal to 1.013 25 bar, or 101 325 Pa.

(*b*) The millimeter of mercury is a legal unit for the measurement of blood pressure in some countries.

(*c*) The ångström is widely used by x-ray crystallographers and structural chemists because all chemical bonds lie in the range 1 to 3 ångströms. However, it has no official sanction from the CIPM or the CGPM.

(*d*) The nautical mile is a special unit employed for marine and aerial navigation to express distance. The conventional value given here was adopted by the First International Extraordinary Hydrographic Conference, Monaco 1929, under the name "International nautical mile." As yet there is no internationally agreed symbol, but the symbols M, NM, Nm, and nmi are all used; in the table the symbol M is used. The unit was originally chosen, and continues to be used, because one nautical mile on the surface of the Earth subtends approximately one minute of angle at the center of the Earth, which is convenient when latitude and longitude are measured in degrees and minutes of angle.

(*e*) The barn is a unit of area employed to express cross sections in nuclear physics.

(*f*) The knot is defined as one nautical mile per hour. There is no internationally agreed symbol, but the symbol kn is commonly used.

(*g*) The statement $L_A = n$ Np (where n is a number) is interpreted to mean that $\ln(A_2/A_1) = n$. Thus when $L_A = 1$ Np, $A_2/A_1 = \mathrm{e}$. The symbol A is used here to denote the amplitude of a sinusoidal signal, and L_A is then called the Napierian logarithmic amplitude ratio, or the Napierian amplitude level difference.

(*h*) The statement $L_X = m$ dB $= (m/10)$ B (where m is a number) is interpreted to mean that $\lg(X/X_0) = m/10$. Thus when $L_X = 1$ B, $X/X_0 = 10$, and when $L_X = 1$ dB, $X/X_0 = 10^{1/10}$. If X denotes a mean square signal or power-like quantity, L_X is called a power level referred to X_0.

(*i*) In using these units it is important that the nature of the quantity be specified, and that any reference value used be specified. These units are not SI units, but they have been accepted by the CIPM for use with the SI.

(*j*) The numerical values of the neper, bel, and decibel (and hence the relation of the bel and the decibel to the neper) are rarely required. They depend on the way in which the logarithmic quantities are defined.

Table 9 differs from Table 8 only in that the units in Table 9 are related to the older CGS (centimeter-gram-second) system of units, including the CGS electrical units. In the field of mechanics, the CGS system of units was built upon three quantities and their corresponding base units: the centimeter, the gram, and the second. The CGS electrical units were still derived from only these same three base units, using defining equations different from those used for the SI. Because this can be done in different ways, it led to the establishment of several different systems, namely the CGS-ESU (electrostatic), the CGS-EMU (electromagnetic), and the CGS-Gaussian unit systems. It has always been recognized that the CGS-Gaussian system, in particular, has advantages in certain areas of physics, particularly in classical and relativistic electrodynamics (9th CGPM, 1948, Resolution 6). Table 9 gives the relations between these CGS units and the SI, and lists those CGS units that were assigned special names. As for the units in Table 8, the SI prefixes are used with several of these units (e.g., millidyne, mdyn; milligauss, mG, etc.).

Table 9. Non-SI units associated with the CGS and the CGS-Gaussian system of units

Quantity	Name of unit	Symbol for unit	Value in SI units
energy	erg [(a)]	erg	1 erg = 10^{-7} J
force	dyne [(a)]	dyn	1 dyn = 10^{-5} N
dynamic viscosity	poise [(a)]	P	1 P = 1 dyn s cm^{-2} = 0.1 Pa s
kinematic viscosity	stokes	St	1 St = 1 cm^2 s^{-1} = 10^{-4} m^2 s^{-1}
luminance	stilb [(a)]	sb	1 sb = 1 cd cm^{-2} = 10^4 cd m^{-2}
illuminance	phot	ph	1 ph = 1 cd sr cm^{-2} = 10^4 lx
acceleration	gal [(b)]	Gal	1 Gal = 1 cm s^{-2} = 10^{-2} m s^{-2}
magnetic flux	maxwell [(c)]	Mx	1 Mx = 1 G cm^2 = 10^{-8} Wb
magnetic flux density	gauss [(c)]	G	1 G = 1 Mx cm^{-2} = 10^{-4} T
magnetic field	œrsted [(c)]	Oe	1 Oe $\hat{=}$ ($10^3/4\pi$) A m^{-1}

(*a*) This unit and its symbol were included in Resolution 7 of the 9th CGPM (1948; CR, 70).

(*b*) The gal is a special unit of acceleration employed in geodesy and geophysics to express acceleration due to gravity.

(*c*) These units are part of the so-called "electromagnetic" three-dimensional CGS system based on unrationalized quantity equations, and must be compared with care to the corresponding unit of the International System which is based on rationalized equations involving four dimensions and four quantities for electromagnetic theory. The magnetic flux, Φ, and the magnetic flux density, B, are defined by similar equations in the CGS system and the SI, so that the corresponding units can be related as in the table. However, the unrationalized magnetic field, H(unrationalized) = $4\pi \times H$(rationalized). The equivalence symbol $\hat{=}$ is used to indicate that when H(unrationalized) = 1 Oe, H(rationalized) = ($10^3/4\pi$) A m^{-1}.

4.2 Other non-SI units not recommended for use

There are many more non-SI units, which are too numerous to list here, which are either of historical interest, or are still used but only in specialized fields (for example, the barrel of oil) or in particular countries (the inch, foot, and yard). The CIPM can see no case for continuing to use these units in modern scientific and technical work. However, it is clearly a matter of importance to be able to recall the relation of these units to the corresponding SI units, and this will continue to be true for many years. The CIPM has therefore decided to compile a list of the conversion factors to the SI for such units and to make this available on the BIPM website at

http://www.bipm.org/en/si/si_brochure/chapter4/conversion_factors.html.

4.3 The curie, roentgen, rad, and rem

This section and Table 10 below have been added to the United States version of the BIPM SI Brochure because, although the curie, roentgen rad, and rem are not accepted by the CIPM for use with the SI, they are widely used in the United States, especially in regulatory documents dealing with health and safety. The interpretation of the SI for the United States given in the *Federal Register* notice referenced in footnote (*f*) of Table 6, p. 32, does in fact accept their use with the SI. Nevertheless, that notice strongly discourages the continued use of the curie, roentgen, rad and rem and recommends that the corresponding SI units should be used whenever possible, with values of relevant quantities given in terms of these outdated units in parentheses only if necessary.

Table 10. The non-SI units curie, roentgen, rad, and rem

Quantity	Name of unit	Symbol for unit	Value in SI units
activity	curie	Ci	1 Ci = 3.7×10^{10} Bq
exposure	roentgen	R	1 R = 2.58×10^{-4} C/kg (air)
absorbed dose	rad	rad [(a)]	1 rad = 1 cGy = 10^{-2} Gy
dose equivalent	rem	rem	1 rem = 1 cSv = 10^{-2} Sv

(*a*) The unit symbol rd may be used in place of rad if there is risk of confusion of this symbol with the unit symbol for the radian.

5 Writing unit symbols and names, and expressing the values of quantities

General principles for the writing of unit symbols and numbers were first given by the 9th CGPM (1948, Resolution 7). These were subsequently elaborated by ISO, IEC, and other international bodies. As a consequence, there now exists a general consensus on how unit symbols and names, including prefix symbols and names, as well as quantity symbols should be written and used, and how the values of quantities should be expressed. Compliance with these rules and style conventions, the most important of which are presented in this chapter, supports the readability of scientific and technical papers.

5.1 Unit symbols

Unit symbols are printed in roman (upright) type regardless of the type used in the surrounding text. They are printed in lower-case letters unless they are derived from a proper name, in which case the first letter is a capital letter.

m, meter
s, second
Pa, pascal
Ω, ohm

An exception, adopted by the 16th CGPM (1979, Resolution 6), is that either capital L or lower-case l is allowed for the liter, in order to avoid possible confusion between the numeral 1 (one) and the lower-case letter l (el). [**Editors' note:** the symbol L is preferred in the United states; see footnote (*f*) of Table 6, p. 32.]

L, liter

A multiple or sub-multiple prefix, if used, is part of the unit and precedes the unit symbol without a separator. A prefix is never used in isolation, and compound prefixes are never used.

nm, ***not*** mμm

Unit symbols are mathematical entities and not abbreviations. Therefore, they are not followed by a period except at the end of a sentence, and one must neither use the plural nor mix unit symbols and unit names within one expression, since names are not mathematical entities.

It is 75 cm long,
not 75 cm. long

l = 75 cm,
not 75 cms

coulomb per kilogram,
not coulomb per kg

In forming products and quotients of unit symbols the normal rules of algebraic multiplication or division apply. Multiplication must be indicated by a space or a half-high (centered) dot (·), since otherwise some prefixes could be misinterpreted as a unit symbol. Division is indicated by a horizontal line, by a solidus (oblique stroke, /) or by negative exponents. When several unit symbols are combined, care should be taken to avoid ambiguities, for example by using brackets or negative exponents. A solidus must not be used more than once in a given expression without brackets to remove ambiguities.

N m or N · m
for a newton meter

m/s or $\frac{\mathrm{m}}{\mathrm{s}}$ or m s^{-1},
for meter per second

ms, millisecond
m s, meter times second

m kg/(s^3 A),
or m kg s^{-3} A^{-1},
but not m kg/s^3/A,
nor m kg/s^3 A

It is not permissible to use abbreviations for unit symbols or unit names, such as sec (for either s or second), sq. mm (for either mm^2 or square millimeter), cc (for either cm^3 or cubic centimeter), or mps (for either m/s or meter per second). The use of the correct symbols for SI units, and for units in general, as listed in earlier chapters of this Brochure, is mandatory. In this way ambiguities and misunderstandings in the values of quantities are avoided.

5.2 Unit names

Unit names are normally printed in roman (upright) type, and they are treated like ordinary nouns. In English, the names of units start with a lower-case letter (even when the symbol for the unit begins with a capital letter), except at the beginning of a sentence or in capitalized material such as a title. In keeping with this rule, the correct spelling of the name of the unit with the symbol °C is "degree Celsius" (the unit degree begins with a lower-case d and the modifier Celsius begins with an upper-case C because it is a proper name).

unit name	symbol
joule	J
hertz	Hz
meter	m
second	s
ampere	A
watt	W

Although the values of quantities are normally expressed using symbols for numbers and symbols for units, if for some reason the unit name is more appropriate than the unit symbol, the unit name should be spelled out in full.

2.6 m/s,
or 2.6 meters per second

When the name of a unit is combined with the name of a multiple or sub-multiple prefix, no space or hyphen is used between the prefix name and the unit name. The combination of prefix name plus unit name is a single word. See also Chapter 3, Section 3.1.

milligram,
but not milli-gram

kilopascal,
but not kilo-pascal

In both English and in French, however, when the name of a derived unit is formed from the names of individual units by multiplication, then either a space or a hyphen is used to separate the names of the individual units.

pascal second, or
pascal-second

In both English and in French modifiers such as "squared" or "cubed" are used in the names of units raised to powers, and they are placed after the unit name. However, in the case of area or volume, as an alternative the modifiers "square" or "cubic" may be used, and these modifiers are placed before the unit name, but this applies only in English.

meter per second squared,
square centimeter,
cubic millimeter,
ampere per square meter,
kilogram per cubic meter.

5.3 Rules and style conventions for expressing values of quantities

5.3.1 Value and numerical value of a quantity, and the use of quantity calculus

The value of a quantity is expressed as the product of a number and a unit, and the number multiplying the unit is the numerical value of the quantity expressed in that unit. The numerical value of a quantity depends on the choice of unit. Thus the value of a particular quantity is independent of the choice of unit, although the numerical value will be different for different units.

The same value of a speed $\upsilon = \mathrm{d}x/\mathrm{d}t$ of a particle might be given by either of the expressions $\upsilon = 25$ m/s $= 90$ km/h, where 25 is the numerical value of the speed in the unit meters per second, and 90 is the numerical value of the speed in the unit kilometers per hour.

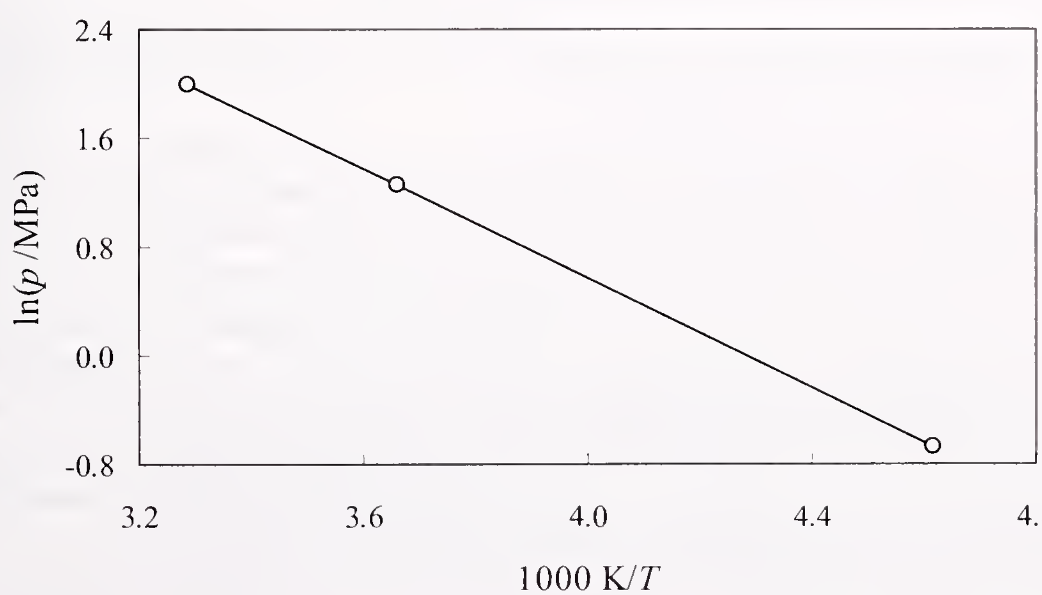
Symbols for quantities are generally single letters set in an italic font, although they may be qualified by further information in subscripts or superscripts or in brackets. Thus C is the recommended symbol for heat capacity, C_m for molar heat capacity, $C_{\mathrm{m},p}$ for molar heat capacity at constant pressure, and $C_{\mathrm{m},V}$ for molar heat capacity at constant volume.

Recommended names and symbols for quantities are listed in many standard references, such as the ISO Standard 31 *Quantities and Units*, the IUPAP SUNAMCO Red Book *Symbols, Units and Nomenclature in Physics*, and the IUPAC Green Book *Quantities, Units and Symbols in Physical Chemistry*. However, symbols for quantities are recommendations (in contrast to symbols for units, for which the use of the correct form is mandatory). In particular circumstances authors may wish to use a symbol of their own choice for a quantity, for example in order to avoid a conflict arising from the use of the same symbol for two different quantities. In such cases, the meaning of the symbol must be clearly stated. However, neither the name of a quantity, nor the symbol used to denote it, should imply any particular choice of unit.

Symbols for units are treated as mathematical entities. In expressing the value of a quantity as the product of a numerical value and a unit, both the numerical value and the unit may be treated by the ordinary rules of algebra. This procedure is described as the use of quantity calculus, or the algebra of quantities. For example, the equation $T = 293$ K may equally be written $T/\mathrm{K} = 293$. It is often convenient to write the quotient of a quantity and a unit in this way for the heading of a column in a table, so that the entries in the table are all simply numbers. For example, a table of vapour pressure against temperature, and the natural logarithm of vapour pressure against reciprocal temperature, may be formatted as shown below.

T/K	$10^3\ \mathrm{K}/T$	p/MPa	$\ln(p/\mathrm{MPa})$
216.55	4.6179	0.5180	−0.6578
273.15	3.6610	3.4853	1.2486
304.19	3.2874	7.3815	1.9990

The axes of a graph may also be labelled in this way, so that the tick marks are labelled only with numbers, as in the graph below.



Algebraically equivalent forms may be used in place of 1000 K/T, such as 10^3 K/T, kK/T, or 10^3 (T/K)$^{-1}$.

5.3.2 Quantity symbols and unit symbols

Just as the quantity symbol should not imply any particular choice of unit, the unit symbol should not be used to provide specific information about the quantity, and should never be the sole source of information on the quantity. Units are never qualified by further information about the nature of the quantity; any extra information on the nature of the quantity should be attached to the quantity symbol and not to the unit symbol.

For example:
The maximum electric potential difference is U_{max} = 1000 V
but not U = 1000 V_{max}.
The mass fraction of copper in the sample of silicon is w(Cu) = 1.3 × 10^{-6}
but not 1.3 × 10^{-6} w/w.

5.3.3 Formatting the value of a quantity

The numerical value always precedes the unit, and a space is always used to separate the unit from the number. Thus the value of the quantity is the product of the number and the unit, the space being regarded as a multiplication sign (just as a space between units implies multiplication). The only exceptions to this rule are for the unit symbols for degree, minute, and second for plane angle, °, ′, and ″, respectively, for which no space is left between the numerical value and the unit symbol.

m = 12.3 g, where m is used as a symbol for the quantity mass, but φ = 30° 22′ 8″, where φ is used as a symbol for the quantity plane angle.

This rule means that the symbol °C for the degree Celsius is preceded by a space when one expresses values of Celsius temperature t.

t = 30.2 °C,
but not t = 30.2°C,
nor t = 30.2° C

Even when the value of a quantity is used as an adjective, a space is left between the numerical value and the unit symbol. Only when the name of the unit is spelled out would the ordinary rules of grammar apply, so that in English a hyphen would be used to separate the number from the unit.

a 10 kΩ resistor

a 35-millimeter film

In any one expression, only one unit is used. An exception to this rule is in expressing the values of time and of plane angles using non-SI units. However, for plane angles it is generally preferable to divide the degree decimally. Thus one would write 22.20° rather than 22° 12′, except in fields such as navigation, cartography, astronomy, and in the measurement of very small angles.

l = 10.234 m,
but not
l = 10 m 23.4 cm

5.3.4 Formatting numbers, and the decimal marker

The symbol used to separate the integral part of a number from its decimal part is called the decimal marker. Following the 22nd CGPM (2003, Resolution 10), the decimal marker "shall be either the point on the line or the comma on the line." The decimal marker chosen should be that which is customary in the context concerned.

If the number is between +1 and −1, then the decimal marker is always preceded by a zero.

−0.234,
but not −.234

Following the 9th CGPM (1948, Resolution 7) and the 22nd CGPM (2003, Resolution 10), for numbers with many digits the digits may be divided into groups of three by a thin space, in order to facilitate reading. Neither dots nor commas are inserted in the spaces between groups of three. However, when there are only four digits before or after the decimal marker, it is customary not to use a space to isolate

43 279.168 29,
but not 43,279.168,29

either 3279.1683
or 3 279.168 3

a single digit. The practice of grouping digits in this way is a matter of choice; it is not always followed in certain specialized applications such as engineering drawings, financial statements, and scripts to be read by a computer.

For numbers in a table, the format used should not vary within one column.

5.3.5 Expressing the measurement uncertainty in the value of a quantity

The uncertainty that is associated with the estimated value of a quantity should be evaluated and expressed in accordance with the *Guide to the Expression of Uncertainty in Measurement* [ISO, 1995]. The standard uncertainty (i.e. estimated standard deviation, coverage factor $k = 1$) associated with a quantity x is denoted by $u(x)$. A convenient way to represent the uncertainty is given in the following example:

$$m_\mathrm{n} = 1.674\ 927\ 28(29) \times 10^{-27}\ \mathrm{kg}.$$

where m_n is the symbol for the quantity (in this case the mass of a neutron), and the number in parenthesis is the numerical value of the combined standard uncertainty of the estimated value of m_n referred to the last two digits of the quoted value; in this case $u(m_\mathrm{n}) = 0.000\ 000\ 29 \times 10^{-27}$ kg. If any coverage factor, k, different from one, is used, this factor must be stated.

5.3.6 Multiplying or dividing quantity symbols, the values of quantities, or numbers

When multiplying or dividing quantity symbols any of the following methods may be used: ab, $a\ b$, $a \cdot b$, $a \times b$, a/b, $\dfrac{a}{b}$, $a\ b^{-1}$.

When multiplying the value of quantities either a multiplication sign, ×, or brackets should be used, not a half-high (centered) dot. When multiplying numbers only the multiplication sign, ×, should be used.

When dividing the values of quantities using a solidus, brackets are used to remove ambiguities.

Examples:

$F = ma$ for force equals mass times acceleration

(53 m/s) × 10.2 s
or (53 m/s)(10.2 s)

25 × 60.5
but not 25 · 60.5

(20 m)/(5 s) = 4 m/s

$(a/b)/c$, ***not*** $a/b/c$

5.3.7 Stating values of dimensionless quantities, or quantities of dimension one

As discussed in Section 2.2.3, the coherent SI unit for dimensionless quantities, also termed quantities of dimension one, is the number one, symbol 1. Values of such quantities are expressed simply as numbers. The unit symbol 1 or unit name "one" are not explicitly shown, nor are special symbols or names given to the unit one, apart from a few exceptions as follows. For the quantity plane angle, the unit one is given the special name radian, symbol rad, and for the quantity solid angle, the unit one is given the special name steradian, symbol sr. For the logarithmic ratio quantities, the special names neper, symbol Np, bel, symbol B, and decibel, symbol dB, are used (see 4.1 and Table 8, p. 35).

$n = 1.51$,
but not $n = 1.51 \times 1$,
where n is the quantity symbol for refractive index.

Because SI prefix symbols can neither be attached to the symbol 1 nor to the name "one," powers of 10 are used to express the values of particularly large or small dimensionless quantities.

In mathematical expressions, the internationally recognized symbol % (percent) may be used with the SI to represent the number 0.01. Thus, it can be used to express the values of dimensionless quantities. When it is used, a space separates the number and the symbol %. In expressing the values of dimensionless quantities in this way, the symbol % should be used rather than the name "percent."

$x_B = 0.0025 = 0.25$ %, where x_B is the quantity symbol for amount fraction (mole fraction) of entity B.

The mirror reflects 95 % of the incident photons.

In written text, however, the symbol % generally takes the meaning of "parts per hundred."

$\varphi = 3.6$ %, ***but not*** $\varphi = 3.6$ % (V/V), where φ denotes volume fraction.

Phrases such as "percentage by mass," "percentage by volume," or "percentage by amount of substance" should not be used; the extra information on the quantity should instead be conveyed in the name and symbol for the quantity.

$x_B = 2.5 \times 10^{-3}$ $= 2.5$ mmol/mol

In expressing the values of dimensionless fractions (e.g. mass fraction, volume fraction, relative uncertainties), the use of a ratio of two units of the same kind is sometimes useful.

$u_r(U) = 0.3$ µV/V, where $u_r(U)$ is the relative uncertainty of the measured voltage U.

The term "ppm," meaning 10^{-6} relative value, or 1 in 10^6, or parts per million, is also used. This is analogous to the meaning of percent as parts per hundred. The terms "parts per billion," and "parts per trillion," and their respective abbreviations "ppb," and "ppt," are also used, but their meanings are language dependent. For this reason the terms ppb and ppt are best avoided. (In English-speaking countries, a billion is now generally taken to be 10^9 and a trillion to be 10^{12}; however, a billion may still sometimes be interpreted as 10^{12} and a trillion as 10^{18}. The abbreviation ppt is also sometimes read as parts per thousand, adding further confusion.)

When any of the terms %, ppm, etc., are used it is important to state the dimensionless quantity whose value is being specified.†

† Editors' note: The NIST policy on the proper way to employ the International System of Units to express the values of quantities does not allow the use of parts per million, parts per billion or parts per trillion and the like, nor the abbreviations ppm, ppb or ppt and the like. Further, it only allows the use of the word "percent" and the symbol % to mean the number 0.01 in the expression of the value of a quantity. See NIST SP 811, available as noted in the Foreword.

Appendix 1. Decisions of the CGPM and the CIPM

This appendix lists those decisions of the CGPM and the CIPM that bear directly upon definitions of the units of the SI, prefixes defined for use as part of the SI, and conventions for the writing of unit symbols and numbers. It is not a complete list of CGPM and CIPM decisions. For a complete list, reference must be made to successive volumes of the *Comptes Rendus des Séances de la Conférence Générale des Poids et Mesures* (CR) and *Procès-Verbaux des Séances du Comité International des Poids et Mesures* (PV) or, for recent decisions, to *Metrologia*.

Since the SI is not a static convention, but evolves following developments in the science of measurement, some decisions have been abrogated or modified; others have been clarified by additions. Decisions that have been subject to such changes are identified by an asterisk (*) and are linked by a note to the modifying decision.

The original text of each decision (or its translation) is shown in a different font (sans serif) of normal weight to distinguish it from the main text. The asterisks and notes were added by the BIPM to make the text more understandable. They do not form part of the original text.

The decisions of the CGPM and CIPM are listed in this appendix in strict chronological order, from 1889 to 2005, in order to preserve the continuity with which they were taken. However in order to make it easy to locate decisions related to particular topics a table of contents is included below, ordered by subject, with page references to the particular meetings at which decisions relating to each subject were taken.

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1st CGPM, 1889

■ Sanction of the international prototypes of the meter and the kilogram (CR, 34-38)*

The Conférence Générale des Poids et Mesures,

considering

- the "Compte rendu of the President of the Comité International des Poids et Mesures (CIPM)" and the "Report of the CIPM," which show that, by the collaboration of the French section of the International Meter Commission and of the CIPM, the fundamental measurements of the international and national prototypes of the meter and of the kilogram have been made with all the accuracy and reliability which the present state of science permits;
- that the international and national prototypes of the meter and the kilogram are made of an alloy of platinum with 10 per cent iridium, to within 0.0001;
- the equality in length of the international Meter and the equality in mass of the international Kilogram with the length of the Meter and the mass of the Kilogram kept in the Archives of France;
- that the differences between the national Meters and the international Meter lie within 0.01 millimeter and that these differences are based on a hydrogen thermometer scale which can always be reproduced thanks to the stability of hydrogen, provided identical conditions are secured;
- that the differences between the national Kilograms and the international Kilogram lie within 1 milligram;
- that the international Meter and Kilogram and the national Meters and Kilograms fulfil the requirements of the Meter Convention,

sanctions

A. As regards international prototypes:

1. The Prototype of the meter chosen by the CIPM. This prototype, at the temperature of melting ice, shall henceforth represent the metric unit of length.
2. The Prototype of the kilogram adopted by the CIPM. This prototype shall henceforth be considered as the unit of mass.
3. The hydrogen thermometer centigrade scale in terms of which the equations of the prototype Meters have been established.

B. As regards national prototypes: .....

...

* The definition of the meter was abrogated in 1960 by the 11th CGPM (Resolution 6, see p. 57).

3rd CGPM, 1901

■ Declaration concerning the definition of the liter (CR, 38-39)*

...

The Conference declares

1. The unit of volume, for high accuracy determinations, is the volume occupied by a mass of 1 kilogram of pure water, at its maximum density and at standard atmospheric pressure: this volume is called "liter."
2. ...

* This definition was abrogated in 1964 by the 12th CGPM (Resolution 6, see p. 61).

■ Declaration on the unit of mass and on the definition of weight; conventional value of g_n (CR, 70)

Taking into account the decision of the Comité International des Poids et Mesures of 15 October 1887, according to which the kilogram has been defined as unit of mass;

Taking into account the decision contained in the sanction of the prototypes of the Metric System, unanimously accepted by the Conférence Générale des Poids et Mesures on 26 September 1889;

Considering the necessity to put an end to the ambiguity which in current practice still exists on the meaning of the word *weight*, used sometimes for *mass*, sometimes for *mechanical force*;

The Conference declares

1. The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram;
2. The word "weight" denotes a quantity of the same nature as a "force": the weight of a body is the product of its mass and the acceleration due to gravity; in particular, the standard weight of a body is the product of its mass and the standard acceleration due to gravity;
3. The value adopted in the International Service of Weights and Measures for the standard acceleration due to gravity is 980.665 cm/s^2, value already stated in the laws of some countries.

Editors' note: In the United States the term "weight" is used to mean both force and mass. In science and technology this declaration is usually followed, with the newton (N) the SI unit of force and thus weight. In commercial and everyday use, and especially in common parlance, weight is often (but incorrectly) used as a synonym for mass, the SI unit of which is the kilogram (kg).

This value of g_n was the conventional reference for calculating the now obsolete unit kilogram force.

7th CGPM, 1927

■ Definition of the meter by the international Prototype (CR, 49)*

The unit of length is the meter, defined by the distance, at 0°, between the axes of the two central lines marked on the bar of platinum-iridium kept at the Bureau International des Poids et Mesures and declared Prototype of the meter by the 1st Conférence Générale des Poids et Mesures, this bar being subject to standard atmospheric pressure and supported on two cylinders of at least one centimeter diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm from each other.

* This definition was abrogated in 1960 by the 11th CGPM (Resolution 6, see p. 57).

CIPM, 1946

■ Definitions of photometric units (PV, **20**, 119-122)*

Resolution

...

4. The photometric units may be defined as follows:

New candle (unit of luminous intensity). — The value of the new candle is such that the brightness of the full radiator at the temperature of solidification of platinum is 60 new candles per square centimeter.

New lumen (unit of luminous flux). — The new lumen is the luminous flux emitted in unit solid angle (steradian) by a uniform point source having a luminous intensity of 1 new candle.

5. ...

* The two definitions contained in this Resolution were ratified in 1948 by the 9th CGPM, which also approved the name candela given to the "new candle" (CR, 54). For the lumen the qualifier "new" was later abandoned. This definition was modified in 1967 by the 13th CGPM (Resolution 5, see p. 63).

■ **Definitions of electric units** (PV, **20**, 132-133)

The definitions contained in this Resolution were ratified in 1948 by the 9th CGPM (CR, 49), which also adopted the name newton (Resolution 7) for the MKS unit of force.

Resolution 2

...

4. (A) Definitions of the mechanical units which enter the definitions of electric units:

Unit of force. — The unit of force [in the MKS (meter, kilogram, second) system] is the force which gives to a mass of 1 kilogram an acceleration of 1 meter per second, per second.

Joule (unit of energy or work). — The joule is the work done when the point of application of 1 MKS unit of force [newton] moves a distance of 1 meter in the direction of the force.

Watt (unit of power). — The watt is the power which in one second gives rise to energy of 1 joule.

(B) Definitions of electric units. The Comité International des Poids et Mesures (CIPM) accepts the following propositions which define the theoretical value of the electric units:

Ampere (unit of electric current). — The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} MKS unit of force [newton] per meter of length.

Volt (unit of potential difference and of electromotive force). — The volt is the potential difference between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

Ohm (unit of electric resistance). — The ohm is the electric resistance between two points of a conductor when a constant potential difference of 1 volt, applied to these points, produces in the conductor a current of 1 ampere, the conductor not being the seat of any electromotive force.

Coulomb (unit of quantity of electricity). — The coulomb is the quantity of electricity carried in 1 second by a current of 1 ampere.

Farad (unit of capacitance). — The farad is the capacitance of a capacitor between the plates of which there appears a potential difference of 1 volt when it is charged by a quantity of electricity of 1 coulomb.

Henry (unit of electric inductance). — The henry is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at the rate of 1 ampere per second.

Weber (unit of magnetic flux). — The weber is the magnetic flux which, linking a circuit of one turn, would produce in it an electromotive force of 1 volt if it were reduced to zero at a uniform rate in 1 second.

9th CGPM, 1948

■ **Triple point of water; thermodynamic scale with a single fixed point; unit of quantity of heat (joule)** (CR, 55 and 63)

Resolution 3

1. With present-day techniques, the triple point of water is capable of providing a thermometric reference point with an accuracy higher than can be obtained from the melting point of ice.

In consequence the Comité Consultatif de Thermométrie et Calorimétrie (CCTC) considers that the zero of the centesimal thermodynamic scale must be defined as the temperature 0.0100 degree below that of the triple point of water.

2. The CCTC accepts the principle of an absolute thermodynamic scale with a single fundamental fixed point, at present provided by the triple point of pure water, the absolute temperature of which will be fixed at a later date.

   The introduction of this new scale does not affect in any way the use of the International Scale, which remains the recommended practical scale.

3. The unit of quantity of heat is the joule.

Note: It is requested that the results of calorimetric experiments be as far as possible expressed in joules. If the experiments are made by comparison with the rise of temperature of water (and that, for some reason, it is not possible to avoid using the calorie), the information necessary for conversion to joules must be provided. The CIPM, advised by the CCTC, should prepare a table giving, in joules per degree, the most accurate values that can be obtained from experiments on the specific heat of water.

A table, prepared in response to this request, was approved and published by the CIPM in 1950 (PV, **22**, 92).

■ Adoption of "degree Celsius" [CIPM, 1948 (PV, 21, 88) and 9th CGPM, 1948 (CR, 64)]

From three names ("degree centigrade," "centesimal degree," "degree Celsius") proposed to denote the degree of temperature, the CIPM has chosen "degree Celsius" (PV, **21**, 88).

This name is also adopted by the 9th CGPM (CR, 64).

■ Proposal for establishing a practical system of units of measurement (CR, 64)

Resolution 6

The Conférence Générale des Poids et Mesures (CGPM),

considering

- that the Comité International des Poids et Mesures (CIPM) has been requested by the International Union of Physics to adopt for international use a practical Système International d'Unités; that the International Union of Physics recommends the MKS system and one electric unit of the absolute practical system, but does not recommend that the CGS system be abandoned by physicists;
- that the CGPM has itself received from the French Government a similar request, accompanied by a draft to be used as basis of discussion for the establishment of a complete specification of units of measurement;

instructs the CIPM:

- to seek by an energetic, active, official enquiry the opinion of scientific, technical and educational circles of all countries (offering them, in fact, the French document as basis);
- to gather and study the answers;
- to make recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the Meter Convention.

■ Writing and printing of unit symbols and of numbers (CR, 70)*

* The CGPM abrogated certain decisions on units and terminology, in particular: micron, degree absolute, and the terms "degree," and "deg," 13th CGPM, 1967/68 (Resolutions 7 and 3, see pp. 64 and 62, respectively), and the liter; 16th CGPM, 1979 (Resolution 6, see p. 69).

Resolution 7

Principles

Roman (upright) type, in general lower-case, is used for symbols of units; if, however, the symbols are derived from proper names, capital roman type is used. These symbols are not followed by a full stop.

In numbers, the comma (French practice) or the dot (British practice) is used only to separate the integral part of numbers from the decimal part. Numbers may be divided in groups of three in order to facilitate reading; neither dots nor commas are ever inserted in the spaces between groups.

Unit	Symbol	Unit	Symbol
• meter	m	ampere	A
• square meter	m^2	volt	V
• cubic meter	m^3	watt	W
• micron	μ	ohm	Ω
• liter	l	coulomb	C
• gram	g	farad	F
• metric ton	t	henry	H
second	s	hertz	Hz
erg	erg	poise	P
dyne	dyn	newton	N
degree Celsius	°C	• candela (new candle)	cd
• degree absolute	°K	lux	lx
calorie	cal	lumen	lm
bar	bar	stilb	sb
hour	h		

Editors' note: The name "tonne" appears in the original text, not "metric ton"; see footnote (g) of Table 6, p. 32.

Notes

1. The symbols whose unit names are preceded by dots are those which had already been adopted by a decision of the CIPM.
2. The symbol for the stere, the unit of volume for firewood, shall be "st" and not "s," which had been previously assigned to it by the CIPM.
3. To indicate a temperature interval or difference, rather than a temperature, the word "degree" in full, or the abbreviation "deg," must be used.

10th CGPM, 1954

■ Definition of the thermodynamic temperature scale (CR, 79)*

* The 13th CGPM in 1967 explicitly defined the kelvin (Resolution 4, see p. 63).

Resolution 3

The 10th Conférence Générale des Poids et Mesures decides to define the thermodynamic temperature scale by choosing the triple point of water as the fundamental fixed point, and assigning to it the temperature 273.16 degrees Kelvin, exactly.

■ Definition of the standard atmosphere (CR, 79)

Resolution 4

The 10th Conférence Générale des Poids et Mesures (CGPM), having noted that the definition of the standard atmosphere given by the 9th CGPM when defining the International Temperature Scale led some physicists to believe that this definition of the standard atmosphere was valid only for accurate work in thermometry,

declares that it adopts, for general use, the definition:

1 standard atmosphere = 1 013 250 dynes per square centimeter,

i.e., 101 325 newtons per square meter.

■ Practical system of units (CR, 80)*

Resolution 6

In accordance with the wish expressed by the 9th Conférence Générale des Poids et Mesures (CGPM) in its Resolution 6 concerning the establishment of a practical system of units of measurement for international use, the 10th CGPM

decides to adopt as base units of the system, the following units:

length	meter
mass	kilogram
time	second
electric current	ampere
thermodynamic temperature	degree Kelvin
luminous intensity	candela

* The unit name "degree kelvin" was changed to "kelvin" in 1967 by the 13th CGPM (Resolution 3, see p. 62).

CIPM, 1956

■ Definition of the unit of time (second) (PV, **25**, 77)*

Resolution 1

In virtue of the powers invested in it by Resolution 5 of the 10th Conférence Générale des Poids et Mesures, the Comité International des Poids et Mesures,

considering

1. that the 9th General Assembly of the International Astronomical Union (Dublin, 1955) declared itself in favour of linking the second to the tropical year,
2. that, according to the decisions of the 8th General Assembly of the International Astronomical Union (Rome, 1952), the second of ephemeris time (ET) is the fraction

$$\frac{12\ 960\ 276\ 813}{408\ 986\ 496} \times 10^{-9} \text{ of the tropical year for 1900 January 0 at 12 h ET,}$$

decides

* This definition was abrogated in 1967 by the 13th CGPM (Resolution 1, see p. 62).

"The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time."

■ **Système International d'Unités** (PV, **25**, 83)

Resolution 3

The Comité International des Poids et Mesures,

considering

- the task entrusted to it by Resolution 6 of the 9th Conférence Générale des Poids et Mesures (CGPM) concerning the establishment of a practical system of units of measurement suitable for adoption by all countries adhering to the Meter Convention,
- the documents received from twenty-one countries in reply to the enquiry requested by the 9th CGPM,
- Resolution 6 of the 10th CGPM, fixing the base units of the system to be established,

recommends

1. that the name "Système International d'Unités" be given to the system founded on the base units adopted by the 10th CGPM, viz.:

   [This is followed by the list of the six base units with their symbols, reproduced in Resolution 12 of the 11th CGPM (1960)].

2. that the units listed in the table below be used, without excluding others which might be added later:

   [This is followed by the table of units reproduced in paragraph 4 of Resolution 12 of the 11th CGPM (1960)].

11th CGPM, 1960

■ **Definition of the meter** (CR, 85)*

* This definition was abrogated in 1983 by the 17th CGPM (Resolution 1, see p. 70).

Resolution 6

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the international Prototype does not define the meter with an accuracy adequate for the present needs of metrology,
- that it is moreover desirable to adopt a natural and indestructible standard,

decides

1. The meter is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton 86 atom.
2. The definition of the meter in force since 1889, based on the international Prototype of platinum-iridium, is abrogated.
3. The international Prototype of the meter sanctioned by the 1st CGPM in 1889 shall be kept at the BIPM under the conditions specified in 1889.

■ Definition of the unit of time (second) (CR, 86)*

* This definition was abrogated in 1967 by the 13th CGPM (Resolution 1, see p. 62).

Resolution 9

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- the powers given to the Comité International des Poids et Mesures (CIPM) by the 10th CGPM to define the fundamental unit of time,
- the decision taken by the CIPM in 1956,

ratifies the following definition:

"The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time."

■ Système International d'Unités (CR, 87)*

* The CGPM later abrogated certain of its decisions and extended the list of prefixes, see notes below.

Resolution 12

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- Resolution 6 of the 10th CGPM, by which it adopted six base units on which to establish a practical system of measurement for international use:

length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	degree Kelvin	°K
luminous intensity	candela	cd

The name and symbol for the unit of thermodynamic temperature was modified by the 13th CGPM in 1967 (Resolution 3, see p. 62).

- Resolution 3 adopted by the Comité International des Poids et Mesures (CIPM) in 1956,
- the recommendations adopted by the CIPM in 1958 concerning an abbreviation for the name of the system, and prefixes to form multiples and submultiples of the units,

decides

1. the system founded on the six base units above is called the "Système International d'Unités";
2. the international abbreviation of the name of the system is: SI;
3. names of multiples and submultiples of the units are formed by means of the following prefixes:

A seventh base unit, the mole, was adopted by the 14th CGPM in 1971 (Resolution 3, see p. 66).

Multiplying factor	Prefix	Symbol	Multiplying factor	Prefix	Symbol
1 000 000 000 000 = 10^{12}	tera	T	0.1 = 10^{-1}	deci	d
1 000 000 000 = 10^{9}	giga	G	0.01 = 10^{-2}	centi	c
1 000 000 = 10^{6}	mega	M	0.001 = 10^{-3}	milli	m
1 000 = 10^{3}	kilo	k	0.000 001 = 10^{-6}	micro	µ
100 = 10^{2}	hecto	h	0.000 000 001 = 10^{-9}	nano	n
10 = 10^{1}	deka	da	0.000 000 000 001 = 10^{-12}	pico	p

Further prefixes were adopted by the 12th CGPM in 1964 (Resolution 8, see p. 61), the 15th CGPM in 1975 (Resolution 10, see p. 67) and the 19th CGPM in 1991 (Resolution 4, see p. 74).

4. the units listed below are used in the system, without excluding others which might be added later.

Supplementary units

plane angle	radian	rad	
solid angle	steradian	sr	

The 20th CGPM in 1995 abrogated the class of supplementary units in the SI (Resolution 8, see p. 74). These are now considered as derived units.

Derived units

area	square meter	m^2	
volume	cubic meter	m^3	
frequency	hertz	Hz	1/s
mass density (density)	kilogram per cubic meter	kg/m^3	
speed, velocity	meter per second	m/s	
angular velocity	radian per second	rad/s	
acceleration	meter per second squared	m/s^2	
angular acceleration	radian per second squared	rad/s^2	
force	newton	N	$kg \cdot m/s^2$
pressure (mechanical stress)	newton per square meter	N/m^2	
kinematic viscosity	square meter per second	m^2/s	
dynamic viscosity	newton-second per square meter	$N \cdot s/m^2$	
work, energy, quantity of heat	joule	J	$N \cdot m$
power	watt	W	J/s
quantity of electricity (side bar)	coulomb	C	$A \cdot s$
tension (voltage), potential difference, electromotive force	volt	V	W/A
electric field strength	volt per meter	V/m	
electric resistance	ohm	Ω	V/A
capacitance	farad	F	$A \cdot s/V$
magnetic flux	weber	Wb	$V \cdot s$
inductance	henry	H	$V \cdot s/A$
magnetic flux density	tesla	T	Wb/m^2
magnetic field strength	ampere per meter	A/m	
magnetomotive force	ampere	A	
luminous flux	lumen	lm	$cd \cdot sr$
luminance	candela per square meter	cd/m^2	
illuminance	lux	lx	lm/m^2

The 13th CGPM in 1967 (Resolution 6, see p. 64) specified other units which should be added to the list. In principle, this list of derived units is without limit.

Modern practice is to use the phrase "amount of heat" rather than "quantity of heat," because the word quantity has a different meaning in metrology.

Modern practice is to use the phrase "amount of electricity" rather than "quantity of electricity" (see note above).

■ **Cubic decimeter and liter** (CR, 88)

Resolution 13

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the cubic decimeter and the liter are unequal and differ by about 28 parts in 10^6,
- that determinations of physical quantities which involve measurements of volume are being made more and more accurately, thus increasing the risk of confusion between the cubic decimeter and the liter,

requests the Comité International des Poids et Mesures to study the problem and submit its conclusions to the 12th CGPM.

CIPM, 1961

■ **Cubic decimeter and liter** (PV, **29**, 34)

Recommendation

The Comité International des Poids et Mesures recommends that the results of accurate measurements of volume be expressed in units of the International System and not in liters.

CIPM, 1964

■ **Atomic and molecular frequency standards** (PV, **32**, 26 and CR, 93)

Declaration

The Comité International des Poids et Mesures,

empowered by Resolution 5 of the 12th Conférence Générale des Poids et Mesures to name atomic or molecular frequency standards for temporary use for time measurements in physics,

declares that the standard to be employed is the transition between the hyperfine levels $F = 4$, $M = 0$ and $F = 3$, $M = 0$ of the ground state $^2S_{1/2}$ of the cesium 133 atom, unperturbed by external fields, and that the frequency of this transition is assigned the value 9 192 631 770 hertz.

12th CGPM, 1964

■ **Atomic standard of frequency** (CR, 93)

Resolution 5

The 12th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the 11th CGPM noted in its Resolution 10 the urgency, in the interests of accurate metrology, of adopting an atomic or molecular standard of time interval,
- that, in spite of the results already obtained with cesium atomic frequency standards, the time has not yet come for the CGPM to adopt a new definition of the second, base

unit of the Système International d'Unités, because of the new and considerable improvements likely to be obtained from work now in progress,

considering also that it is not desirable to wait any longer before time measurements in physics are based on atomic or molecular frequency standards,

empowers the Comité International des Poids et Mesures to name the atomic or molecular frequency standards to be employed for the time being,

requests the organizations and laboratories knowledgeable in this field to pursue work connected with a new definition of the second.

■ **Liter** (CR, 93)

Resolution 6

The 12th Conférence Générale des Poids et Mesures (CGPM),

considering Resolution 13 adopted by the 11th CGPM in 1960 and the Recommendation adopted by the Comité International des Poids et Mesures in 1961,

1. **abrogates** the definition of the liter given in 1901 by the 3rd CGPM,
2. **declares** that the word "liter" may be employed as a special name for the cubic decimeter,
3. **recommends** that the name liter should not be employed to give the results of high-accuracy volume measurements.

■ **Curie** (CR, 94)*

* The name "becquerel" (Bq) was adopted by the 15th CGPM in 1975 (Resolution 8, see p. 67) for the SI unit of activity: 1 Ci = 3.7×10^{10} Bq.

Resolution 7

The 12th Conférence Générale des Poids et Mesures,

considering that the curie has been used for a long time in many countries as unit of activity for radionuclides,

recognizing that in the Système International d'Unités (SI), the unit of this activity is the second to the power of minus one (s^{-1}),

accepts that the curie be still retained, outside SI, as unit of activity, with the value $3.7 \times 10^{10}\ s^{-1}$. The symbol for this unit is Ci.

■ **SI prefixes femto and atto** (CR, 94)*

* New prefixes were added by the 15th CGPM in 1975 (Resolution 10, see p. 67).

Resolution 8

The 12th Conférence Générale des Poids et Mesures (CGPM)

decides to add to the list of prefixes for the formation of names of multiples and sub-multiples of units, adopted by the 11th CGPM, Resolution 12, paragraph 3, the following two new prefixes:

Multiplying factor	Prefix	Symbol
10^{-15}	femto	f
10^{-18}	atto	a

CIPM, 1967

■ **Decimal multiples and submultiples of the unit of mass** (PV, **35**, 29 and *Metrologia*, 1968, **4**, 45)

Recommendation 2

The Comité International des Poids et Mesures,

considering that the rule for forming names of decimal multiples and submultiples of the units of paragraph 3 of Resolution 12 of the 11th Conférence Générale des Poids et Mesures (CGPM) (1960) might be interpreted in different ways when applied to the unit of mass,

declares that the rules of Resolution 12 of the 11th CGPM apply to the kilogram in the following manner: the names of decimal multiples and submultiples of the unit of mass are formed by attaching prefixes to the word “gram.”

13th CGPM, 1967/68

■ **SI unit of time (second)** (CR, 103 and *Metrologia*, 1968, **4**, 43)

Resolution 1

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the definition of the second adopted by the Comité International des Poids et Mesures (CIPM) in 1956 (Resolution 1) and ratified by Resolution 9 of the 11th CGPM (1960), later upheld by Resolution 5 of the 12th CGPM (1964), is inadequate for the present needs of metrology,
- that at its meeting of 1964 the CIPM, empowered by Resolution 5 of the 12th CGPM (1964), recommended, in order to fulfil these requirements, a cesium atomic frequency standard for temporary use,
- that this frequency standard has now been sufficiently tested and found sufficiently accurate to provide a definition of the second fulfilling present requirements,
- that the time has now come to replace the definition now in force of the unit of time of the Système International d’Unités by an atomic definition based on that standard,

decides

1. The SI unit of time is the second defined as follows:

   “The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom”;
2. Resolution 1 adopted by the CIPM at its meeting of 1956 and Resolution 9 of the 11th CGPM are now abrogated.

At its 1997 meeting, the CIPM affirmed that this definition refers to a cesium atom at rest at a thermodynamic temperature of 0 K.

■ **SI unit of thermodynamic temperature (kelvin)** (CR, 104 and *Metrologia*, 1968, **4**, 43)*

* At its 1980 meeting, the CIPM approved the report of the 7th meeting of the CCU, which requested that the use of the symbols “°K” and “deg” no longer be permitted.

Resolution 3

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering

- the names "degree Kelvin" and "degree," the symbols "°K" and "deg" and the rules for their use given in Resolution 7 of the 9th CGPM (1948), in Resolution 12 of the 11th CGPM (1960), and the decision taken by the Comité International des Poids et Mesures in 1962 (PV, **30**, 27),
- that the unit of thermodynamic temperature and the unit of temperature interval are one and the same unit, which ought to be denoted by a single name and a single symbol,

decides

1. the unit of thermodynamic temperature is denoted by the name "kelvin" and its symbol is "K";**
2. the same name and the same symbol are used to express a temperature interval;
3. a temperature interval may also be expressed in degrees Celsius;
4. the decisions mentioned in the opening paragraph concerning the name of the unit of thermodynamic temperature, its symbol and the designation of the unit to express an interval or a difference of temperatures are abrogated, but the usages which derive from these decisions remain permissible for the time being.

** See Recommendation 2 (CI-2005) of the CIPM on the isotopic composition of water entering in the definition of the kelvin, p. 80.

■ **Definition of the SI unit of thermodynamic temperature (kelvin)** (CR, 104 and *Metrologia*, 1968, **4**, 43)*

* See Recommendation 5 (CI-1989) of the CIPM on the International Temperature Scale of 1990, p. 73.

Resolution 4

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering that it is useful to formulate more explicitly the definition of the unit of thermodynamic temperature contained in Resolution 3 of the 10th CGPM (1954),

decides to express this definition as follows:

"The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water."

■ **SI unit of luminous intensity (candela)** (CR, 104 and *Metrologia*, 1968, **4**, 43-44)*

* This definition was abrogated by the 16th CGPM in 1979 (Resolution 3, see p. 68).

Resolution 5

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering

- the definition of the unit of luminous intensity ratified by the 9th CGPM (1948) and contained in the "Resolution concerning the change of photometric units" adopted by the Comité International des Poids et Mesures in 1946 (PV, **20**, 119) in virtue of the powers conferred by the 8th CGPM (1933),
- that this definition fixes satisfactorily the unit of luminous intensity, but that its wording may be open to criticism,

decides to express the definition of the candela as follows:

"The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square meter of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square meter."

■ **SI derived units** (CR, 105 and *Metrologia*, 1968, **4**, 44)*

Resolution 6

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering that it is useful to add some derived units to the list of paragraph 4 of Resolution 12 of the 11th CGPM (1960),

decides to add:

wave number	1 per meter	m^{-1}
entropy	joule per kelvin	J/K
specific heat capacity	joule per kilogram kelvin	J/(kg · K)
thermal conductivity	watt per meter kelvin	W/(m · K)
radiant intensity	watt per steradian	W/sr
activity (of a radioactive source)	1 per second	s^{-1}

* The unit of activity was given a special name and symbol by the 15th CGPM in 1975 (Resolution 8, see p. 67).

■ **Abrogation of earlier decisions (micron and new candle)** (CR, 105 and *Metrologia*, 1968, **4**, 44)

Resolution 7

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering that subsequent decisions of the General Conference concerning the Système International d'Unités are incompatible with parts of Resolution 7 of the 9th CGPM (1948),

decides accordingly to remove from Resolution 7 of the 9th Conference:

1. the unit name "micron," and the symbol "μ" which had been given to that unit but which has now become a prefix;
2. the unit name "new candle."

CIPM, 1969

■ **Système International d'Unités, Rules for application of Resolution 12 of the 11th CGPM (1960)** (PV, **37**, 30 and *Metrologia*, 1970, **6**, 66)*

Recommendation 1

The Comité International des Poids et Mesures,

considering that Resolution 12 of the 11th Conférence Générale des Poids et Mesures (CGPM) (1960), concerning the Système International d'Unités, has provoked discussions on certain of its aspects,

declares

1. the base units, the supplementary units and the derived units of the Système International d'Unités, which form a coherent set, are denoted by the name "SI units";**
2. the prefixes adopted by the CGPM for the formation of decimal multiples and submultiples of SI units are called "SI prefixes";

and **recommends**

3. the use of SI units and of their decimal multiples and submultiples whose names are formed by means of SI prefixes.

* The 20th CGPM in 1995 decided to abrogate the class of supplementary units in the SI (Resolution 8, see p. 74).

** The CIPM approved in 2001 a proposal of the CCU to clarify the definition of "SI units" and "units of the SI," see p. 76.

Note: The name "supplementary units," appearing in Resolution 12 of the 11th CGPM (and in the present Recommendation) is given to SI units for which the General Conference declines to state whether they are base units or derived units.

CCDS, 1970 (*In* CIPM, 1970)

■ **Definition of TAI** (PV, **38**, 110-111 and *Metrologia*, 1971, **7**, 43)

Recommendation S 2

International Atomic Time (TAI) is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units.

In 1980, the definition of TAI was completed as follows (declaration of the CCDS, *BIPM Com. Cons. Déf. Seconde*, 1980, **9**, S 15 and *Metrologia*, 1981, **17**, 70):

TAI is a coordinate time scale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit.

This definition was further amplified by the International Astronomical Union in 1991, Resolution A4: "TAI is a realized time scale whose ideal form, neglecting a constant offset of 32.184 s, is Terrestrial Time (TT), itself related to the time coordinate of the geocentric reference frame, Geocentric Coordinate Time (TCG), by a constant rate." (See Proc. 21st General Assembly of the IAU, *IAU Trans.*, 1991, vol. **XXIB**, Kluwer.)

14th CGPM, 1971

■ **Pascal and siemens** (CR, 78)

The 14th Conférence Générale des Poids et Mesures adopted the special names "pascal" (symbol Pa), for the SI unit newton per square meter, and "siemens" (symbol S), for the SI unit of electric conductance [reciprocal ohm].

■ **International Atomic Time, function of CIPM** (CR, 77-78 and *Metrologia*, 1972, **8**, 35)

Resolution 1

The 14th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the second, unit of time of the Système International d'Unités, has since 1967 been defined in terms of a natural atomic frequency, and no longer in terms of the time scales provided by astronomical motions,
- that the need for an International Atomic Time (TAI) scale is a consequence of the atomic definition of the second,
- that several international organizations have ensured and are still successfully ensuring the establishment of the time scales based on astronomical motions, particularly thanks to the permanent services of the Bureau International de l'Heure (BIH),
- that the BIH has started to establish an atomic time scale of recognized quality and proven usefulness,
- that the atomic frequency standards for realizing the second have been considered and must continue to be considered by the Comité International des Poids et Mesures (CIPM) helped by a Consultative Committee, and that the unit interval of the International Atomic Time scale must be the second realized according to its atomic definition,

- that all the competent international scientific organizations and the national laboratories active in this field have expressed the wish that the CIPM and the CGPM should give a definition of International Atomic Time, and should contribute to the establishment of the International Atomic Time scale,
- that the usefulness of International Atomic Time entails close coordination with the time scales based on astronomical motions,

requests the CIPM

1. to give a definition of International Atomic Time,
2. to take the necessary steps, in agreement with the international organizations concerned, to ensure that available scientific competence and existing facilities are used in the best possible way to realize the International Atomic Time scale and to satisfy the requirements of users of International Atomic Time.

The definition of TAI was given by the CCDS in 1970 (now the CCTF), see p. 65.

■ **SI unit of amount of substance (mole)** (CR, 78 and *Metrologia*, 1972, **8**, 36)*

* At its 1980 meeting, the CIPM approved the report of the 7th meeting of the CCU (1980) specifying that, in this definition, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to.

Resolution 3

The 14th Conférence Générale des Poids et Mesures (CGPM),

considering the advice of the International Union of Pure and Applied Physics, of the International Union of Pure and Applied Chemistry, and of the International Organization for Standardization, concerning the need to define a unit of amount of substance,

decides

1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is “mol.”
2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
3. The mole is a base unit of the Système International d’Unités.

15th CGPM, 1975

■ **Recommended value for the speed of light** (CR, 103 and *Metrologia*, 1975, **11**, 179-180)

Resolution 2

The 15th Conférence Générale des Poids et Mesures,

considering the excellent agreement among the results of wavelength measurements on the radiations of lasers locked on a molecular absorption line in the visible or infrared region, with an uncertainty estimated at $\pm 4 \times 10^{-9}$ which corresponds to the uncertainty of the realization of the meter,

The relative uncertainty given here corresponds to three standard deviations in the data considered.

considering also the concordant measurements of the frequencies of several of these radiations,

recommends the use of the resulting value for the speed of propagation of electromagnetic waves in vacuum c = 299 792 458 meters per second.

■ **Coordinated Universal Time (UTC)** (CR, 104 and *Metrologia*, 1975, **11**, 180)

Resolution 5

The 15th Conférence Générale des Poids et Mesures,

considering that the system called "Coordinated Universal Time" (UTC) is widely used, that it is broadcast in most radio transmissions of time signals, that this wide diffusion makes available to the users not only frequency standards but also International Atomic Time and an approximation to Universal Time (or, if one prefers, mean solar time),

notes that this Coordinated Universal Time provides the basis of civil time, the use of which is legal in most countries,

judges that this usage can be strongly endorsed.

■ **SI units for ionizing radiation (becquerel and gray)** (CR, 105 and *Metrologia*, 1975, **11**, 180)*

Resolutions 8 and 9

The 15th Conférence Générale des Poids et Mesures,

by reason of the pressing requirement, expressed by the International Commission on Radiation Units and Measurements (ICRU), to extend the use of the Système International d'Unités to radiological research and applications,

by reason of the need to make as easy as possible the use of the units for nonspecialists,

taking into consideration also the grave risks of errors in therapeutic work,

adopts the following special name for the SI unit of activity:

becquerel, symbol Bq, equal to one reciprocal second (Resolution 8),

adopts the following special name for the SI unit of ionizing radiation:

gray, symbol Gy, equal to one joule per kilogram (Resolution 9).

Note: The gray is the SI unit of absorbed dose. In the field of ionizing radiation, the gray may be used with other physical quantities also expressed in joules per kilogram: the Comité Consultatif des Unités has responsibility for studying this matter in collaboration with the competent international organizations.

* At its 1976 meeting, the CIPM approved the report of the 5th meeting of the CCU (1976), specifying that, following the advice of the ICRU, the gray may also be used to express specific energy imparted, kerma and absorbed dose index.

■ **SI prefixes peta and exa** (CR, 106 and *Metrologia*, 1975, **11**, 180-181)*

Resolution 10

The 15th Conférence Générale des Poids et Mesures (CGPM)

decides to add to the list of SI prefixes to be used for multiples, which was adopted by the 11th CGPM, Resolution 12, paragraph 3, the two following prefixes:

Multiplying factor	Prefix	Symbol
10^{15}	peta	P
10^{18}	exa	E

* New prefixes were added by the 19th CGPM in 1991 (Resolution 4, see p. 74).

16th CGPM, 1979

■ **SI unit of luminous intensity (candela)** (CR, 100 and *Metrologia*, 1980, **16**, 56)

Resolution 3

The 16th Conférence Générale des Poids et Mesures (CGPM),

considering

- that despite the notable efforts of some laboratories there remain excessive divergences between the results of realizations of the candela based upon the present black body primary standard,
- that radiometric techniques are developing rapidly, allowing precisions that are already equivalent to those of photometry and that these techniques are already in use in national laboratories to realize the candela without having to construct a black body,
- that the relation between luminous quantities of photometry and radiometric quantities, namely the value of 683 lumens per watt for the spectral luminous efficacy of monochromatic radiation of frequency 540×10^{12} hertz, has been adopted by the Comité International des Poids et Mesures (CIPM) in 1977,
- that this value has been accepted as being sufficiently accurate for the system of luminous photopic quantities, that it implies a change of only about 3 % for the system of luminous scotopic quantities, and that it therefore ensures satisfactory continuity,
- that the time has come to give the candela a definition that will allow an improvement in both the ease of realization and the precision of photometric standards, and that applies to both photopic and scotopic photometric quantities and to quantities yet to be defined in the mesopic field,

Photopic vision is detected by the cones on the retina of the eye, which are sensitive to a high level of luminance ($L >$ ca. 10 cd/m^2) and are used in daytime vision. Scotopic vision is detected by the rods of the retina, which are sensitive to low level luminance ($L <$ ca. 10^{-3} cd/m^2), used in night vision. In the domain between these levels of luminance both cones and rods are used, and this is described as mesopic vision.

decides

1. The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.
2. The definition of the candela (at the time called new candle) adopted by the CIPM in 1946 by reason of the powers conferred by the 8th CGPM in 1933, ratified by the 9th CGPM in 1948, then amended by the 13th CGPM in 1967, is abrogated.

■ **Special name for the SI unit of dose equivalent (sievert)** (CR, 100 and *Metrologia*, 1980, **16**, 56)*

* The CIPM, in 1984, decided to accompany this Resolution with an explanation (Recommendation 1, see p. 71).

Resolution 5

The 16th Conférence Générale des Poids et Mesures,

considering

- the effort made to introduce SI units into the field of ionizing radiations,
- the risk to human beings of an underestimated radiation dose, a risk that could result from a confusion between absorbed dose and dose equivalent,
- that the proliferation of special names represents a danger for the Système International d'Unités and must be avoided in every possible way, but that this rule can be broken when it is a matter of safeguarding human health,

adopts the special name ***sievert***, symbol Sv, for the SI unit of dose equivalent in the field of radioprotection. The sievert is equal to the joule per kilogram.

■ **Symbols for the liter** (CR, 101 and *Metrologia*, 1980, **16**, 56-57)

Resolution 6

The 16th Conférence Générale des Poids et Mesures (CGPM),

recognizing the general principles adopted for writing the unit symbols in Resolution 7 of the 9th CGPM (1948),

considering that the symbol l for the unit liter was adopted by the Comité International des Poids et Mesures (CIPM) in 1879 and confirmed in the same Resolution of 1948,

considering also that, in order to avoid the risk of confusion between the letter l and the number 1, several countries have adopted the symbol L instead of l for the unit liter,

considering that the name liter, although not included in the Système International d'Unités, must be admitted for general use with the System,

decides, as an exception, to adopt the two symbols l and L as symbols to be used for the unit liter,

considering further that in the future only one of these two symbols should be retained,

invites the CIPM to follow the development of the use of these two symbols and to give the 18th CGPM its opinion as to the possibility of suppressing one of them.

Editors' note: The preferred symbol for the liter in the United states is L; see footnote (*f*) of Table 6, p. 32.

The CIPM, in 1990, considered that it was still too early to choose a single symbol for the liter.

CIPM, 1980

■ **SI supplementary units (radian and steradian)** (PV, **48**, 24 and *Metrologia*, 1981, **17**, 72)*

Recommendation 1

The Comité International des Poids et Mesures (CIPM),

taking into consideration Resolution 3 adopted by ISO/TC 12 in 1978 and Recommendation U 1 (1980) adopted by the Comité Consultatif des Unités at its 7th meeting,

considering

- that the units radian and steradian are usually introduced into expressions for units when there is need for clarification, especially in photometry where the steradian plays an important role in distinguishing between units corresponding to different quantities,
- that in the equations used one generally expresses plane angle as the ratio of two lengths and solid angle as the ratio between an area and the square of a length, and consequently that these quantities are treated as dimensionless quantities,
- that the study of the formalisms in use in the scientific field shows that none exists which is at the same time coherent and convenient and in which the quantities plane angle and solid angle might be considered as base quantities,

considering also

- that the interpretation given by the CIPM in 1969 for the class of supplementary units introduced in Resolution 12 of the 11th Conférence Générale des Poids et Mesures (CGPM) in 1960 allows the freedom of treating the radian and the steradian as SI base units,
- that such a possibility compromises the internal coherence of the SI based on only seven base units,

* The class of SI supplementary units was abrogated by decision of the 20th CGPM in 1995 (Resolution 8, see p. 74).

decides to interpret the class of supplementary units in the International System as a class of dimensionless derived units for which the CGPM allows the freedom of using or not using them in expressions for SI derived units.

17th CGPM, 1983

■ Definition of the meter (CR, 97 and *Metrologia*, 1984, **20**, 25)

Resolution 1

The 17th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the present definition does not allow a sufficiently precise realization of the meter for all requirements,
- that progress made in the stabilization of lasers allows radiations to be obtained that are more reproducible and easier to use than the standard radiation emitted by a krypton 86 lamp,
- that progress made in the measurement of the frequency and wavelength of these radiations has resulted in concordant determinations of the speed of light whose accuracy is limited principally by the realization of the present definition of the meter,
- that wavelengths determined from frequency measurements and a given value for the speed of light have a reproducibility superior to that which can be obtained by comparison with the wavelength of the standard radiation of krypton 86,
- that there is an advantage, notably for astronomy and geodesy, in maintaining unchanged the value of the speed of light recommended in 1975 by the 15th CGPM in its Resolution 2 (c = 299 792 458 m/s),
- that a new definition of the meter has been envisaged in various forms all of which have the effect of giving the speed of light an exact value, equal to the recommended value, and that this introduces no appreciable discontinuity into the unit of length, taking into account the relative uncertainty of $\pm 4 \times 10^{-9}$ of the best realizations of the present definition of the meter,
- that these various forms, making reference either to the path travelled by light in a specified time interval or to the wavelength of a radiation of measured or specified frequency, have been the object of consultations and deep discussions, have been recognized as being equivalent and that a consensus has emerged in favour of the first form,
- that the Comité Consultatif pour la Définition du Mètre (CCDM) is now in a position to give instructions for the practical realization of such a definition, instructions which could include the use of the orange radiation of krypton 86 used as standard up to now, and which may in due course be extended or revised,

The relative uncertainty given here corresponds to three standard deviations in the data considered.

decides

1. The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second,
2. The definition of the meter in force since 1960, based upon the transition between the levels $2p_{10}$ and $5d_5$ of the atom of krypton 86, is abrogated.

■ **On the realization of the definition of the meter** (CR, 98 and *Metrologia*, 1984, **20**, 25-26)

See Recommendation 1 (CI-2002) of the CIPM on the revision of the practical realization of the definition of the meter, p. 76.

Resolution 2

The 17th Conférence Générale des Poids et Mesures,

invites the Comité International des Poids et Mesures

- to draw up instructions for the practical realization of the new definition of the meter,
- to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and to draw up instructions for their use,
- to pursue studies undertaken to improve these standards.

CIPM, 1984

■ **Concerning the sievert** (PV, **52**, 31 and *Metrologia*, 1985, **21**, 90)*

* The CIPM, in 2002, decided to change the explanation of the quantity dose equivalent in the SI Brochure (Recommendation 2, see p. 78).

Recommendation 1

The Comité International des Poids et Mesures,

considering the confusion which continues to exist on the subject of Resolution 5, approved by the 16th Conférence Générale des Poids et Mesures (1979),

decides to introduce the following explanation in the brochure "Le Système International d'Unités (SI)":

The quantity dose equivalent H is the product of the absorbed dose D of ionizing radiation and the dimensionless factors Q (quality factor) and N (product of any other multiplying factors) stipulated by the International Commission on Radiological Protection:

$$H = Q \cdot N \cdot D \,.$$

Thus, for a given radiation, the numerical value of H in joules per kilogram may differ from that of D in joules per kilogram depending upon the values of Q and N. In order to avoid any risk of confusion between the absorbed dose D and the dose equivalent H, the special names for the respective units should be used, that is, the name gray should be used instead of joules per kilogram for the unit of absorbed dose D and the name sievert instead of joules per kilogram for the unit of dose equivalent H.

18th CGPM, 1987

■ **Forthcoming adjustment to the representations of the volt and of the ohm** (CR, 100 and *Metrologia*, 1988, **25**, 115)

Resolution 6

The 18th Conférence Générale des Poids et Mesures,

considering

- that worldwide uniformity and long-term stability of national representations of the electrical units are of major importance for science, commerce and industry from both the technical and economic points of view,
- that many national laboratories use the Josephson effect and are beginning to use the quantum Hall effect to maintain, respectively, representations of the volt and of the ohm, as these offer the best guarantees of long-term stability,

- that because of the importance of coherence among the units of measurement of the various physical quantities the values adopted for these representations must be as closely as possible in agreement with the SI,
- that the results of recent and current experiment will permit the establishment of an acceptable value, sufficiently compatible with the SI, for the coefficient which relates each of these effects to the corresponding electrical unit,

invites the laboratories whose work can contribute to the establishment of the quotient voltage/frequency in the case of the Josephson effect and of the quotient voltage/current for the quantum Hall effect to vigorously pursue these efforts and to communicate their results without delay to the Comité International des Poids et Mesures, and

instructs the Comité International des Poids et Mesures to recommend, as soon as it considers it possible, a value for each of these quotients together with a date for them to be put into practice simultaneously in all countries; these values should be announced at least one year in advance and would be adopted on 1 January 1990.

CIPM, 1988

■ **Representation of the volt by means of the Josephson effect** (PV, **56**, 44 and *Metrologia*, 1989, **26**, 69)

Recommendation 1

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

- that a detailed study of the results of the most recent determinations leads to a value of 483 597.9 GHz/V for the Josephson constant, K_J, that is to say, for the quotient of frequency divided by the potential difference corresponding to the $n = 1$ step in the Josephson effect,
- that the Josephson effect, together with this value of K_J, can be used to establish a reference standard of electromotive force having a one-standard-deviation uncertainty with respect to the volt estimated to be 4 parts in 10^7, and a reproducibility which is significantly better,

recommends

- that 483 597.9 GHz/V exactly be adopted as a conventional value, denoted by K_{J-90} for the Josephson constant, K_J,
- that this new value be used from 1 January 1990, and not before, to replace the values currently in use,
- that this new value be used from this same date by all laboratories which base their measurements of electromotive force on the Josephson effect, and
- that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with the new adopted value,

is of the opinion that no change in this recommended value of the Josephson constant will be necessary in the foreseeable future, and

draws the attention of laboratories to the fact that the new value is greater by 3.9 GHz/V, or about 8 parts in 10^6, than the value given in 1972 by the Comité Consultatif d'Électricité in its Declaration E-72.

■ **Representation of the ohm by means of the quantum Hall effect** (PV, **56**, 45 and *Metrologia*, 1989, **26**, 70)

At its 89th meeting in 2000, the CIPM approved the declaration of the 22nd meeting of the CCEM on the use of the value of the von Klitzing constant, see p. 76.

Recommendation 2

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

- that most existing laboratory reference standards of resistance change significantly with time,
- that a laboratory reference standard of resistance based on the quantum Hall effect would be stable and reproducible,
- that a detailed study of the results of the most recent determinations leads to a value of 25 812.807 Ω for the von Klitzing constant, R_K, that is to say, for the quotient of the Hall potential difference divided by current corresponding to the plateau $i = 1$ in the quantum Hall effect,
- that the quantum Hall effect, together with this value of R_K, can be used to establish a reference standard of resistance having a one-standard-deviation uncertainty with respect to the ohm estimated to be 2 parts in 10^7, and a reproducibility which is significantly better,

recommends

- that 25 812.807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,
- that this value be used from 1 January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,
- that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with R_{K-90},
- that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edition of the technical guidelines for reliable measurements of the quantized Hall resistance drawn up by the Comité Consultatif d'Électricité and published by the Bureau International des Poids et Mesures, and

is of the opinion that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

CIPM, 1989

■ **The International Temperature Scale of 1990** (PV, **57**, 115 and *Metrologia*, 1990, **27**, 13)

Recommendation 5

The Comité International des Poids et Mesures (CIPM) acting in accordance with Resolution 7 of the 18th Conférence Générale des Poids et Mesures (1987) has adopted the International Temperature Scale of 1990 (ITS-90) to supersede the International Practical Temperature Scale of 1968 (IPTS-68).

The CIPM **notes** that, by comparison with the IPTS-68, the ITS-90

- extends to lower temperatures, down to 0.65 K, and hence also supersedes the EPT-76,
- is in substantially better agreement with corresponding thermodynamic temperatures,
- has much improved continuity, precision and reproducibility throughout its range and
- has subranges and alternative definitions in certain ranges which greatly facilitate its use.

The CIPM also **notes** that, to accompany the text of the ITS-90 there will be two further documents, the *Supplementary Information for the ITS-90* and *Techniques for Approximating the ITS-90*. These documents will be published by the BIPM and periodically updated.

The CIPM **recommends**

- that on 1 January 1990 the ITS-90 come into force and
- that from this same date the IPTS-68 and the EPT-76 be abrogated.

19th CGPM, 1991

■ **SI prefixes zetta, zepto, yotta and yocto** (CR, 185 and *Metrologia*, 1992, **29**, 3)

Resolution 4

The 19th Conférence Générale des Poids et Mesures (CGPM)

decides to add to the list of SI prefixes to be used for multiples and submultiples of units, adopted by the 11th CGPM, Resolution 12, paragraph 3, the 12th CGPM, Resolution 8 and the 15th CGPM, Resolution 10, the following prefixes:

Multiplying factor	Prefix	Symbol
10^{21}	zetta	Z
10^{-21}	zepto	z
10^{24}	yotta	Y
10^{-24}	yocto	y

The names zepto and zetta are derived from septo suggesting the number seven (the seventh power of 10^3) and the letter "z" is substituted for the letter "s" to avoid the duplicate use of the letter "s" as a symbol. The names yocto and yotta are derived from octo, suggesting the number eight (the eighth power of 10^3); the letter "y" is added to avoid the use of the letter "o" as a symbol because it may be confused with the number zero.

20th CGPM, 1995

■ **Elimination of the class of supplementary units in the SI** (CR, 223 and *Metrologia*, 1996, **33**, 83)

Resolution 8

The 20th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the 11th Conférence Générale in 1960 in its Resolution 12, establishing the Système International d'Unités, SI, distinguished between three classes of SI units: the base units, the derived units, and the supplementary units, the last of these comprising the radian and the steradian,
- that the status of the supplementary units in relation to the base units and the derived units gave rise to debate,
- that the Comité International des Poids et Mesures, in 1980, having observed that the ambiguous status of the supplementary units compromises the internal coherence of

the SI, has in its Recommendation 1 (CI-1980) interpreted the supplementary units, in the SI, as dimensionless derived units,

approving the interpretation given by the Comité International in 1980,

decides

- to interpret the supplementary units in the SI, namely the radian and the steradian, as dimensionless derived units, the names and symbols of which may, but need not, be used in expressions for other SI derived units, as is convenient,
- and, consequently, to eliminate the class of supplementary units as a separate class in the SI.

21st CGPM, 1999

■ The definition of the kilogram (CR, 331 and *Metrologia*, 2000, **37**, 94)

Resolution 7

The 21st Conférence Générale des Poids et Mesures,

considering

- the need to assure the long-term stability of the International System of Units (SI),
- the intrinsic uncertainty in the long-term stability of the artifact defining the unit of mass, one of the base units of the SI,
- the consequent uncertainty in the long-term stability of the other three base units of the SI that depend on the kilogram, namely, the ampere, the mole and the candela,
- the progress already made in a number of different experiments designed to link the unit of mass to fundamental or atomic constants,
- the desirability of having more than one method of making such a link,

recommends that national laboratories continue their efforts to refine experiments that link the unit of mass to fundamental or atomic constants with a view to a future redefinition of the kilogram.

■ Special name for the SI derived unit mole per second, the katal, for the expression of catalytic activity (CR, 334-335 and *Metrologia*, 2000, **37**, 95)

Resolution 12

The 21st Conférence Générale des Poids et Mesures,

considering

- the importance for human health and safety of facilitating the use of SI units in the fields of medicine and biochemistry,
- that a non-SI unit called "unit," symbol U, equal to 1 $\mu mol \cdot min^{-1}$, which is not coherent with the International System of Units (SI), has been in widespread use in medicine and biochemistry since 1964 for expressing catalytic activity,
- that the absence of a special name for the SI coherent derived unit mole per second has led to results of clinical measurements being given in various local units,
- that the use of SI units in medicine and clinical chemistry is strongly recommended by the international unions in these fields,

- that the International Federation of Clinical Chemistry and Laboratory Medicine has asked the Consultative Committee for Units to recommend the special name katal, symbol kat, for the SI unit mole per second,
- that while the proliferation of special names represents a danger for the SI, exceptions are made in matters related to human health and safety (15th General Conference, 1975, Resolutions 8 and 9, 16th General Conference, 1979, Resolution 5),

noting that the name katal, symbol kat, has been used for the SI unit mole per second for over thirty years to express catalytic activity,

decides to adopt the special name katal, symbol kat, for the SI unit mole per second to express catalytic activity, especially in the fields of medicine and biochemistry,

and **recommends** that when the katal is used, the measurand be specified by reference to the measurement procedure; the measurement procedure must identify the indicator reaction.

CIPM, 2000

■ "use of the von Klitzing constant to express the value of a reference standard of resistance as a function of quantum Hall effect" (PV, **68**, 101)

At its 89th meeting in 2000, the CIPM approved the following declaration of the 22nd meeting of the CCEM (CCEM, **22**, 90):

"The CCEM, having reviewed the 1998 CODATA least squares adjustment of the fundamental constants, is now of the opinion that the quantum Hall effect, together with the value of R_{K-90}, can be used to establish a reference standard of resistance having a relative one standard deviation uncertainty with respect to the ohm, estimated to be 1×10^{-7}, and a reproducibility which is significantly better. This represents a reduction in the uncertainty of a factor of two compared with the 1988 recommendation."

CIPM, 2001

■ "SI units" and "units of the SI" (PV, **69**, 120)

The CIPM approved in 2001 the following proposal of the CCU regarding "SI units" and "units of the SI":

"We suggest that "SI units" and "units of the SI" should be regarded as names that include both the base units and the coherent derived units, and also all units obtained by combining these with the recommended multiple and sub-multiple prefixes.

We suggest that the name "coherent SI units" should be used when it is desired to restrict the meaning to only the base units and the coherent derived units."

CIPM, 2002

■ Revision of the practical realization of the definition of the meter (PV, **70**, 194-204 and *Metrologia*, **40**, 103-133)

Recommendation 1

The International Committee for Weights and Measures,

recalling

- that in 1983 the 17th General Conference (CGPM) adopted a new definition of the meter;
- that in the same year the CGPM invited the International Committee (CIPM)
  - to draw up instructions for the practical realization of the meter,
  - to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and draw up instructions for their use,
  - to pursue studies undertaken to improve these standards and in due course to extend or revise these instructions;
- that in response to this invitation the CIPM adopted Recommendation 1 (CI-1983) (*mise en pratique* of the definition of the meter) to the effect
  - that the meter should be realized by one of the following methods:

  (a) by means of the length l of the path travelled in vacuum by a plane electromagnetic wave in a time t; this length is obtained from the measured time t, using the relation $l = c_0 \cdot t$ and the value of the speed of light in vacuum c_0 = 299 792 458 m/s,

  (b) by means of the wavelength in vacuum λ of a plane electromagnetic wave of frequency f; this wavelength is obtained from the measured frequency f using the relation $\lambda = c_0/f$ and the value of the speed of light in vacuum c_0 = 299 792 458 m/s,

  (c) by means of one of the radiations from the list below, whose stated wavelength in vacuum or whose stated frequency can be used with the uncertainty shown, provided that the given specifications and accepted good practice are followed;

  - that in all cases any necessary corrections be applied to take account of actual conditions such as diffraction, gravitation or imperfection in the vacuum;
  - that in the context of general relativity, the meter is considered a unit of proper length. Its definition, therefore, applies only within a spatial extent sufficiently small that the effects of the non-uniformity of the gravitational field can be ignored (note that, at the surface of the Earth, this effect in the vertical direction is about 1 part in 10^{16} per meter). In this case, the effects to be taken into account are those of special relativity only. The local methods for the realization of the meter recommended in (b) and (c) provide the proper meter but not necessarily that given in (a). Method (a) should therefore be restricted to lengths l which are sufficiently short for the effects predicted by general relativity to be negligible with respect to the uncertainties of realization. For advice on the interpretation of measurements in which this is not the case, see the report of the Consultative Committee for Time and Frequency (CCTF) Working Group on the Application of General Relativity to Metrology (Application of general relativity to metrology, *Metrologia*, 1997, **34**, 261-290);
- that the CIPM had already recommended a list of radiations for this purpose;

recalling also that in 1992 and in 1997 the CIPM revised the practical realization of the definition of the meter;

considering

- that science and technology continue to demand improved accuracy in the realization of the meter;
- that since 1997 work in national laboratories, in the BIPM and elsewhere has identified new radiations and methods for their realization which lead to lower uncertainties;
- that there is an increasing move towards optical frequencies for time-related activities, and that there continues to be a general widening of the scope of application of the recommended radiations of the *mise en pratique* to cover not only dimensional

metrology and the realization of the meter, but also high-resolution spectroscopy, atomic and molecular physics, fundamental constants and telecommunication;

- that a number of new frequency values with reduced uncertainties for radiations of high-stability cold atom and ion standards already listed in the recommended radiations list are now available, that the frequencies of radiations of several new cold atom and ion species have also recently been measured, and that new improved values with substantially reduced uncertainties for a number of optical frequency standards based on gas cells have been determined, including the wavelength region of interest to optical telecommunications;
- that new femtosecond comb techniques have clear significance for relating the frequency of high-stability optical frequency standards to that of the frequency standard realizing the SI second, that these techniques represent a convenient measurement technique for providing traceability to the International System of Units (SI) and that comb technology also can provide frequency sources as well as a measurement technique;

recognizes comb techniques as timely and appropriate, and recommends further research to fully investigate the capability of the techniques;

welcomes validations now being made of comb techniques by comparison with other frequency chain techniques;

urges national metrology institutes and other laboratories to pursue the comb technique to the highest level of accuracy achievable and also to seek simplicity so as to encourage widespread application;

recommends

- that the list of recommended radiations given by the CIPM in 1997 (Recommendation 1 (CI-1997)) be replaced by the list of radiations given below*, including
  - updated frequency values for cold Ca atom, H atom and the trapped Sr^+ ion,
  - frequency values for new cold ion species including trapped Hg^+ ion, trapped In^+ ion and trapped Yb^+ ion,
  - updated frequency values for Rb-stabilized lasers, I_2-stabilized Nd:YAG and He-Ne lasers, CH_4-stabilized He-Ne lasers and OsO_4-stabilized CO_2 lasers at 10 μm,
  - frequency values for standards relevant to the optical communications bands, including Rb- and C_2H_2-stabilized lasers.

. . .

* The list of recommended radiations, Recommendation 1 (CI-2002), is given in PV, **70**, 197-204 and *Metrologia*, 2003, **40**, 104-115.
Updates are available on the BIPM website at http://www.bipm.org/en/publications/mep.html.

■ **Dose equivalent** (PV, **70**, 205)

See also *J. Radiol. Prot.*, 2005, **25**, 97-100.

Recommendation 2

The International Committee for Weights and Measures,

considering that

- the current definition of the SI unit of dose equivalent (sievert) includes a factor "*N*" (product of any other multiplying factors) stipulated by the International Commission on Radiological Protection (ICRP), and
- both the ICRP and the International Commission on Radiation Units and Measurements (ICRU) have decided to delete this factor *N* as it is no longer deemed to be necessary, and
- the current SI definition of *H* including the factor *N* is causing some confusion,

decides to change the explanation in the brochure "Le Système International d'Unités (SI)" to the following:

The quantity dose equivalent H is the product of the absorbed dose D of ionizing radiation and the dimensionless factor Q (quality factor) defined as a function of linear energy transfer by the ICRU:

$$H = Q \cdot D .$$

Thus, for a given radiation, the numerical value of H in joules per kilogram may differ from that of D in joules per kilogram depending on the value of Q.

The Committee further **decides** to maintain the final sentence in the explanation as follows:

In order to avoid any risk of confusion between the absorbed dose D and the dose equivalent H, the special names for the respective units should be used, that is, the name gray should be used instead of joules per kilogram for the unit of absorbed dose D and the name sievert instead of joules per kilogram for the unit of dose equivalent H.

CIPM, 2003

■ Revision of the *Mise en Pratique* list of recommended radiations (PV, **71**, 146 and *Metrologia*, 2004, **41**, 99-100)

Further updates are available on the BIPM website at http://www.bipm.org/en/publications/mep.html.

Recommendation 1

The International Committee for Weights and Measures,

considering that

- improved frequency values for radiations of some high-stability cold ion standards already documented in the recommended radiations list have recently become available;
- improved frequency values for the infra-red gas-cell-based optical frequency standard in the optical telecommunications region, already documented in the recommended radiations list, have been determined;
- femtosecond comb-based frequency measurements for certain iodine gas-cell standards on the subsidiary recommended source list have recently been made for the first time, leading to significantly reduced uncertainty;

proposes that the *recommended radiation* list be revised to include the following:

- updated frequency values for the single trapped $^{88}Sr^{+}$ ion quadrupole transition and the single trapped $^{171}Yb^{+}$ octupole transition;
- an updated frequency value for the C_2H_2-stabilized standard at 1.54 μm;
- updated frequency values for the I_2-stabilized standards at 543 nm and 515 nm.

22nd CGPM, 2003

■ Symbol for the decimal marker (CR, 381 and *Metrologia*, 2004, **41**, 104)

Resolution 10

The 22nd General Conference,

considering that

- a principal purpose of the International System of Units (SI) is to enable values of quantities to be expressed in a manner that can be readily understood throughout the world,
- the value of a quantity is normally expressed as a number times a unit,

- often the number in the expression of the value of a quantity contains multiple digits with an integral part and a decimal part,
- in Resolution 7 of the 9th General Conference, 1948, it is stated that "In numbers, the comma (French practice) or the dot (British practice) is used only to separate the integral part of numbers from the decimal part,"
- following a decision of the International Committee made at its 86th meeting (1997), the International Bureau of Weights and Measures now uses the dot (point on the line) as the decimal marker in all the English language versions of its publications, including the English text of the SI Brochure (the definitive international reference on the SI), with the comma (on the line) remaining the decimal marker in all of its French language publications,
- however, some international bodies use the comma on the line as the decimal marker in their English language documents,
- furthermore, some international bodies, including some international standards organizations, specify the decimal marker to be the comma on the line in all languages,
- the prescription of the comma on the line as the decimal marker is in many languages in conflict with the customary usage of the point on the line as the decimal marker in those languages,
- in some languages that are native to more than one country, either the point on the line or the comma on the line is used as the decimal marker depending on the country, while in some countries with more than one native language, either the point on the line or comma on the line is used depending on the language,

declares that the symbol for the decimal marker shall be either the point on the line or the comma on the line,

reaffirms that "Numbers may be divided in groups of three in order to facilitate reading; neither dots nor commas are ever inserted in the spaces between groups," as stated in Resolution 7 of the 9th CGPM, 1948.

CIPM, 2005

■ Clarification of the definition of the kelvin, unit of thermodynamic temperature (PV, **94**, in press and *Metrologia*, 2006, **43**, 177-178)

Recommendation 2

The International Committee for Weights and Measures (CIPM),

considering

- that the kelvin, unit of thermodynamic temperature, is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water,
- that the temperature of the triple point depends on the relative amount of isotopes of hydrogen and oxygen present in the sample of water used,
- that this effect is now one of the major sources of the observed variability between different realizations of the water triple point,

decides

- that the definition of the kelvin refer to water of a specified isotopic composition,
- that this composition be:

0.000 155 76 mole of ^{2}H per mole of ^{1}H,

0.000 379 9 mole of ^{17}O per mole of ^{16}O, and

0.002 005 2 mole of ^{18}O per mole of ^{16}O,

which is the composition of the International Atomic Energy Agency reference material Vienna Standard Mean Ocean Water (VSMOW), as recommended by IUPAC in "Atomic Weights of the Elements: Review 2000."

- that this composition be stated in a note attached to the definition of the kelvin in the SI brochure as follows:

  "This definition refers to water having the isotopic composition defined exactly by the following amount of substance ratios: 0.000 155 76 mole of ^{2}H per mole of ^{1}H, 0.000 379 9 mole of ^{17}O per mole of ^{16}O and 0.002 005 2 mole of ^{18}O per mole of ^{16}O."

■ Revision of the *Mise en pratique* list of recommended radiations (PV, 94, in press and *Metrologia*, 2006, **43**, 178)

Recommendation 3

The International Committee for Weights and Measures (CIPM),

considering that:

- improved frequency values for radiations of some high-stability cold ion and cold atom standards already documented in the recommended radiations list have recently become available;
- improved frequency values for the infra-red gas-cell-based optical frequency standard in the optical telecommunications region, already documented in the recommended radiations list, have been determined;
- improved frequency values for certain iodine gas-cell standard, already documented in the subsidiary recommended source list, have been determined;
- frequencies of new cold atoms, of atoms in the near-infrared region and of molecules in the optical telecommunications region have been determined by femtosecond comb-based frequency measurements for the first time;

decides that the list of *recommended radiations* be revised to include the following:

- updated frequency values for the single trapped $^{88}Sr^{+}$ ion quadrupole transition, the single trapped $^{199}Hg^{+}$ quadrupole transition and the single trapped $^{171}Yb^{+}$ quadrupole transition;
- an updated frequency value for the Ca atom transition;
- an updated frequency value for the C_2H_2-stabilized standard at 1.54 μm;
- an updated frequency value for the I_2-stabilized standard at 515 nm;
- the addition of the ^{87}Sr atom transition at 698 nm;
- the addition of the ^{87}Rb atom two-photon transitions at 760 nm;
- the addition of the $^{12}C_2H_2$ ($\nu1 + \nu3$) band and the $^{13}C_2H_2$ ($\nu1 + \nu3$) and ($\nu1 + \nu3 + \nu4 + \nu5$) bands at 1.54 μm.

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Appendix 2. Practical realization of the definitions of some important units

Appendix 2 is published in electronic form only, and is available on the BIPM website at http://www.bipm.org/en/si/si_brochure/appendix2/.

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Appendix 3. Units for photochemical and photobiological quantities

Optical radiation is able to cause chemical changes in certain living or non-living materials: this property is called actinism, and radiation capable of causing such changes is referred to as actinic radiation. Actinic radiation has the fundamental characteristic that, at the molecular level, one photon interacts with one molecule to alter or break the molecule into new molecular species. It is therefore possible to define specific photochemical or photobiological quantities in terms of the result of optical radiation on the associated chemical or biological receptors.

The definition of photometric quantities and units can be found in the *International Lighting Vocabulary*, CIE publication 17.4 (1987) or in the *International Electrotechnical Vocabulary*, IEC publication 50, chapter 845: lighting.

In the field of metrology, the only photobiological quantity which has been formally defined for measurement in the SI is for the interaction of light with the human eye in vision. An SI base unit, the candela, has been defined for this important photobiological quantity. Several other photometric quantities with units derived from the candela have also been defined (such as the lumen and the lux, see Table 3 in Chapter 2, p. 25).

1 Actinic action spectrum

Optical radiation can be characterized by its spectral power distribution. The mechanisms by which optical radiation is absorbed by chemical or biological systems are usually complicated, and are always wavelength (or frequency) dependent. For metrological purposes, however, the complexities of the absorption mechanisms can be ignored, and the actinic effect is characterized simply by an actinic action spectrum linking the photochemical or the photobiological response to the incident radiation. This actinic action spectrum describes the relative effectiveness of monochromatic optical radiation at wavelength λ to elicit a given actinic response. It is given in relative values, normalized to 1 for the maximum of efficacy. Usually actinic action spectra are defined and recommended by international scientific or standardizing organizations.

Principles governing photometry, *Monographie BIPM*, 1983, 32 pp.

For vision, two action spectra have been defined by the CIE and endorsed by the CIPM: $V(\lambda)$ for photopic vision and $V'(\lambda)$ for scotopic vision. These are used in the measurement of photometric quantities and are an implicit part of the definition of the SI unit for photometry, the candela. Photopic vision is detected by the cones on the retina of the eye, which are sensitive to a high level of luminance ($L >$ ca. 10 cd m^{-2}) and are used in daytime vision. Scotopic vision is detected by the rods of the retina, which are sensitive to low level luminance ($L <$ ca. 10^{-3} cd m^{-2}), used in night vision. In the domain between these levels of luminance both cones and rods are used, and this is described as mesopic vision.

Other action spectra for other actinic effects have also been defined by the CIE, such as the erythemal (skin reddening) action spectrum for ultraviolet radiation, but these have not been given any special status within the SI.

2 Measurement of photochemical or photobiological quantities and their corresponding units

The photometric quantities and photometric units which are used at present for vision are well established and have been widely used for a long time. They are not affected by the following rules. For all other photochemical and photobiological quantities the following rules shall be applied for defining the units to be used.

A photochemical or photobiological quantity is defined in purely physical terms as the quantity derived from the corresponding radiant quantity by evaluating the radiation according to its action upon a selective receptor, the spectral sensitivity of which is defined by the actinic action spectrum of the photochemical or photobiological effect considered. The quantity is given by the integral over wavelength of the spectral distribution of the radiant quantity weighted by the appropriate actinic action spectrum. The use of integrals implicitly assumes a law of arithmetic additivity for actinic quantities, although such a law is not perfectly obeyed by actual actinic effects. The action spectrum is a relative quantity; it is dimensionless, with the SI unit one. The radiant quantity has the radiometric unit corresponding to that quantity. Thus, following the rule for obtaining the SI unit for a derived quantity, the unit of the photochemical or photobiological quantity is the radiometric unit of the corresponding radiant quantity. When giving a quantitative value, it is essential to specify whether a radiometric or actinic quantity is intended as the unit is the same. If an actinic effect exists in several action spectra, the action spectrum used for measurement has to be clearly specified.

This method of defining the units to be used for photochemical or photobiological quantities has been recommended by the Consultative Committee for Photometry and Radiometry at its 9th meeting in 1977.

As an example, the erythemal effective irradiance E_{er} from a source of ultraviolet radiation is obtained by weighting the spectral irradiance of the radiation at wavelength λ by the effectiveness of radiation at this wavelength to cause an erythema, and summing over all wavelengths present in the source spectrum. This can be expressed mathematically as

$$E_{\mathrm{er}} = \int E_\lambda s_{\mathrm{er}}(\lambda)\mathrm{d}\lambda\,,$$

where E_λ is the spectral irradiance at wavelength λ (usually reported in the SI unit $\mathrm{W\,m^{-2}\,nm^{-1}}$), and $s_{\mathrm{er}}(\lambda)$ is the actinic spectrum normalized to 1 at its maximum spectral value. The erythemal irradiance E_{er} determined in this way is usually quoted in the SI unit $\mathrm{W\,m^{-2}}$.

List of acronyms used in the present volume

1 Acronyms for laboratories, committees and conferences*

BAAS	British Association for the Advancement of Science
BIH	*Bureau International de l'Heure*
BIPM	International Bureau of Weights and Measures/*Bureau International des Poids et Mesures*
CARICOM	Carribean Community
CCAUV	Consultative Committee for Acoustics, Ultrasound and Vibration/*Comité Consultatif de l'Acoustique, des Ultrasons et des Vibrations*
CCDS*	Consultative Committee for the Definition of the Second/*Comité Consultatif pour la Définition de la Seconde*, see CCTF
CCE*	Consultative Committee for Electricity/*Comité Consultatif d'Électricité*, see CCEM
CCEM	(formerly the CCE) Consultative Committee for Electricity and Magnetism/*Comité Consultatif d'Électricité et Magnétisme*
CCL	Consultative Committee for Length/*Comité Consultatif des Longueurs*
CCM	Consultative Committee for Mass and Related Quantities/*Comité Consultatif pour la Masse et les Grandeurs Apparentées*
CCPR	Consultative Committee for Photometry and Radiometry/*Comité Consultatif de Photométrie et Radiométrie*
CCQM	Consultative Committee for Amount of Substance: Metrology in Chemistry/*Comité Consultatif pour la Quantité de Matière: Métrologie en Chimie*
CCRI	Consultative Committee for Ionizing Radiation/*Comité Consultatif des Rayonnements Ionisants*
CCT	Consultative Committee for Thermometry/*Comité Consultatif de Thermométrie*
CCTF	(formerly the CCDS) Consultative Committee for Time and Frequency/*Comité Consultatif du Temps et des Fréquences*
CCU	Consultative Committee for Units/*Comité Consultatif des Unités*
CGPM	General Conference on Weights and Measures/*Conférence Générale des Poids et Mesures*
CIE	International Commission on Illumination/*Commission Internationale de l'Éclairage*
CIPM	International Committee for Weights and Measures/*Comité International des Poids et Mesures*

* Organizations marked with an asterisk either no longer exist or operate under a different acronym.

CODATA	Committee on Data for Science and Technology
CR	*Comptes Rendus* of the *Conférence Générale des Poids et Mesures*, CGPM
IAU	International Astronomical Union
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IEC	International Electrotechnical Commission/*Commission Électrotechnique Internationale*
IERS	International Earth Rotation and Reference Systems Service
ISO	International Organization for Standardization
IUPAC	International Union of Pure and Applied Chemistry
IUPAP	International Union of Pure and Applied Physics
OIML	*Organisation Internationale de Métrologie Légale*
PV	*Procès-Verbaux* of the *Comité International des Poids et Mesures*, CIPM
SUNAMCO	Commission for Symbols, Units, Nomenclature, Atomic Masses, and Fundamental Constants, IUPAP
WHO	World Health Organization

2 Acronyms for scientific terms

CGS	Three-dimensional coherent system of units based on the three mechanical units centimeter, gram, and second
EPT-76	Provisional Low Temperature Scale of 1976/*Échelle provisoire de température de 1976*
IPTS-68	International Practical Temperature Scale of 1968
ITS-90	International Temperature Scale of 1990
MKS	System of units based on the three mechanical units meter, kilogram, and second
MKSA	Four-dimensional system of units based on the meter, kilogram, second, and the ampere
SI	International System of Units/*Système International d'Unités*
TAI	International Atomic Time/*Temps Atomique International*
TCG	Geocentric Coordinated Time/*Temps-coordonnée Géocentrique*
TT	Terrestrial Time
UTC	Coordinated Universal Time
VSMOW	Vienna Standard Mean Ocean Water

Index

Numbers in boldface indicate the pages where the definitions of the units, or terms, are to be found.